The NOνA Experiment

P5

Fermilab

18 April 2006

Gary Feldman

NOνA:
NuMI Off-Axis ν_e Appearance Experiment

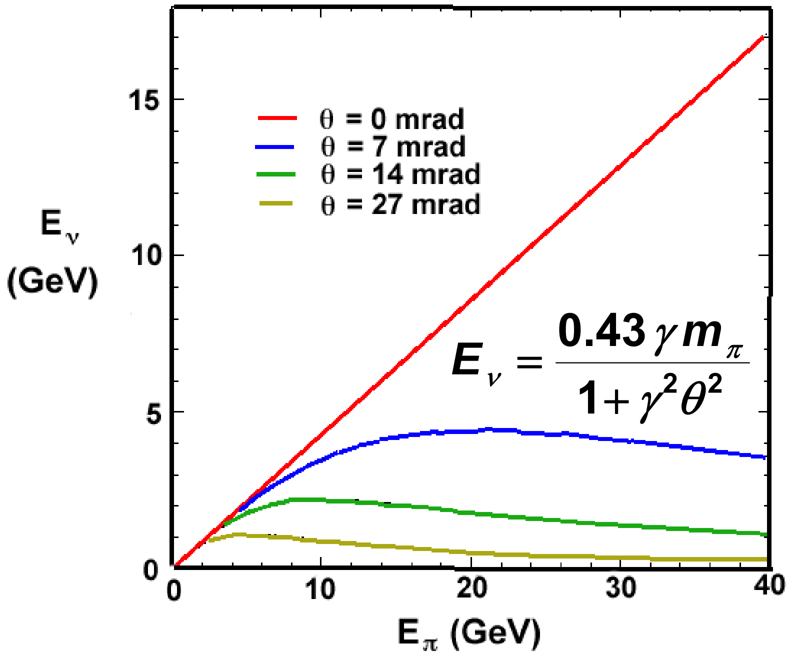
- NOνA is a proposed 2nd generation experiment on the NuMI beamline. Its Far Detector will be a 25 kT totally active, tracking liquid scintillator calorimeter located near Ash River, MN, 810 km from Fermilab and 12 km off the center of the NuMI beamline.
- Its main physics goal will be the study of $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric oscillation length.
- Its unique characteristic is its long baseline, which allows access to matter effects, which can be used to determine the ordering of the neutrino mass states.

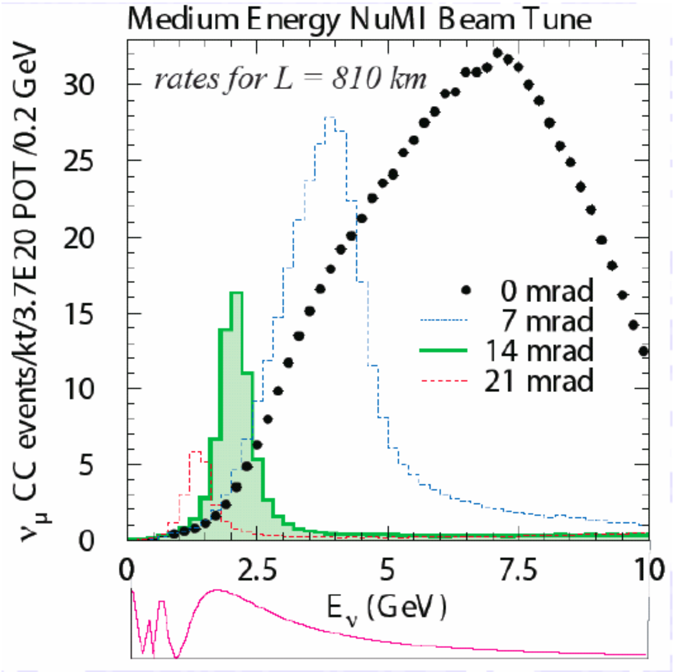
The NOνA Collaboration

- The NOνA Collaboration consists of 142 physicists and engineers from 28 institutions:
  - Argonne, Athens, Caltech, College de France, Fermilab, Harvard, Indiana, ITEP, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, Northern Illinois, Ohio, Ohio State, Oxford, Rutherford, Rio de Janeiro, South Carolina, SMU, Stanford, Texas, Texas A&M, Tufts, UCLA, Virginia, Washington, William and Mary
- Five Italian universities with about 20 senior physicists are actively discussing joining NOνA.
- Based on MINOS experience, we expect to have about 50 students when the experiment runs.

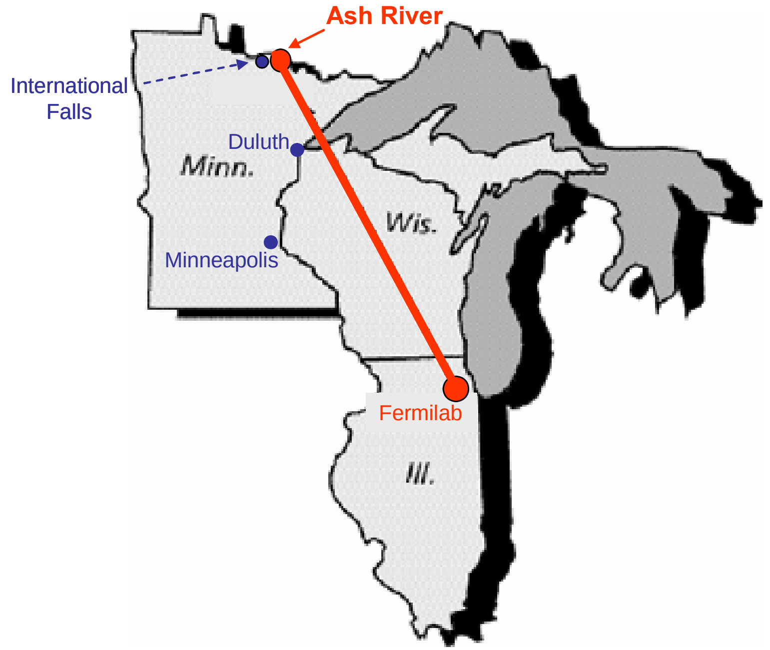
Why Off-Axis?

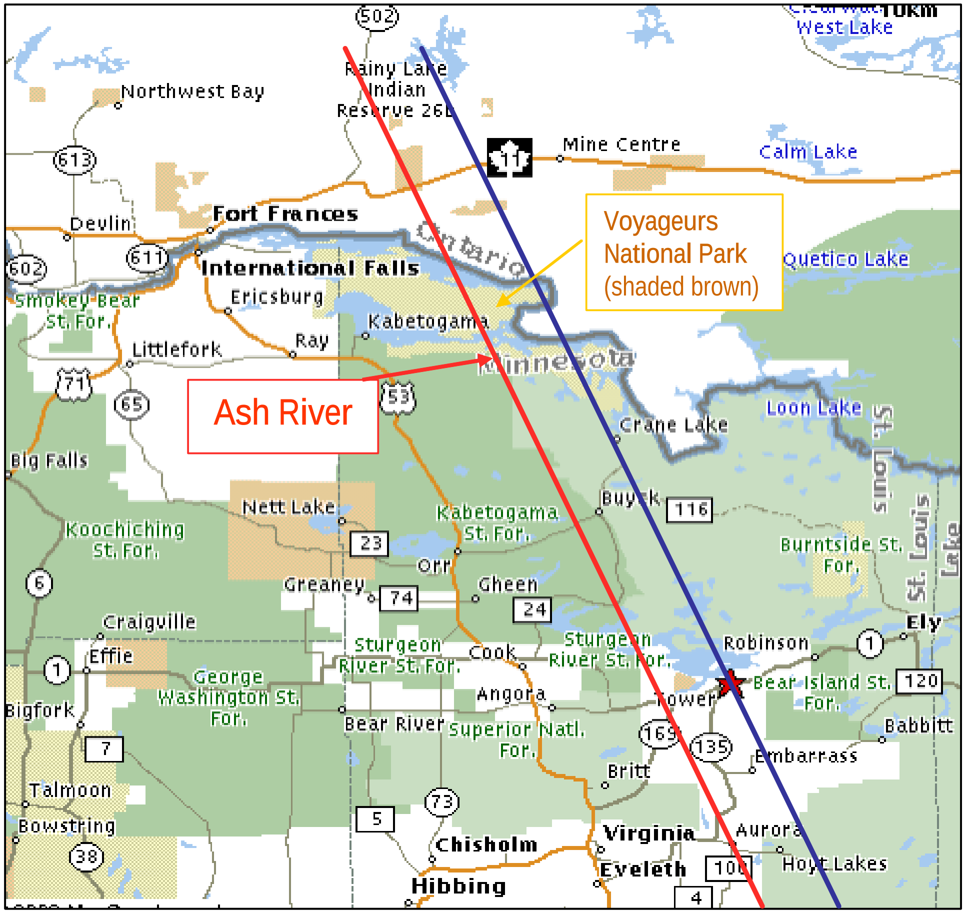
- **Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:**
  - **More flux and less background (ν_e's from *K* decay and higher-energy NC events)**





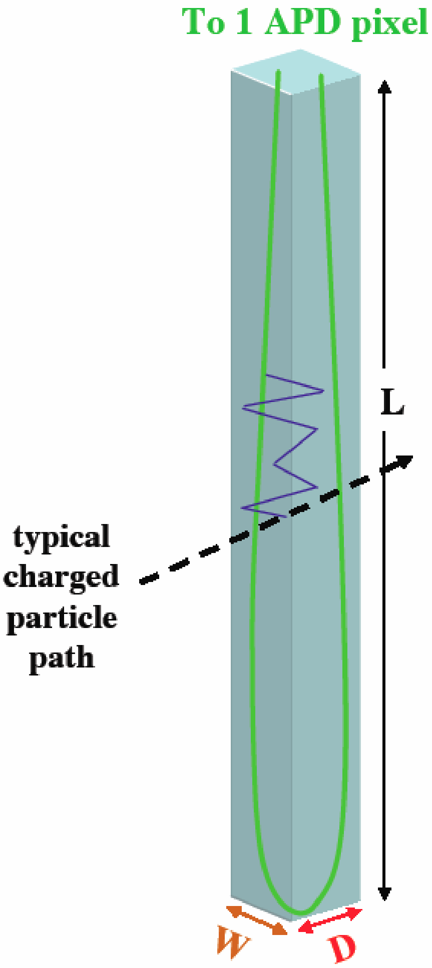
Why Ash River?





The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

Basic Detector Element

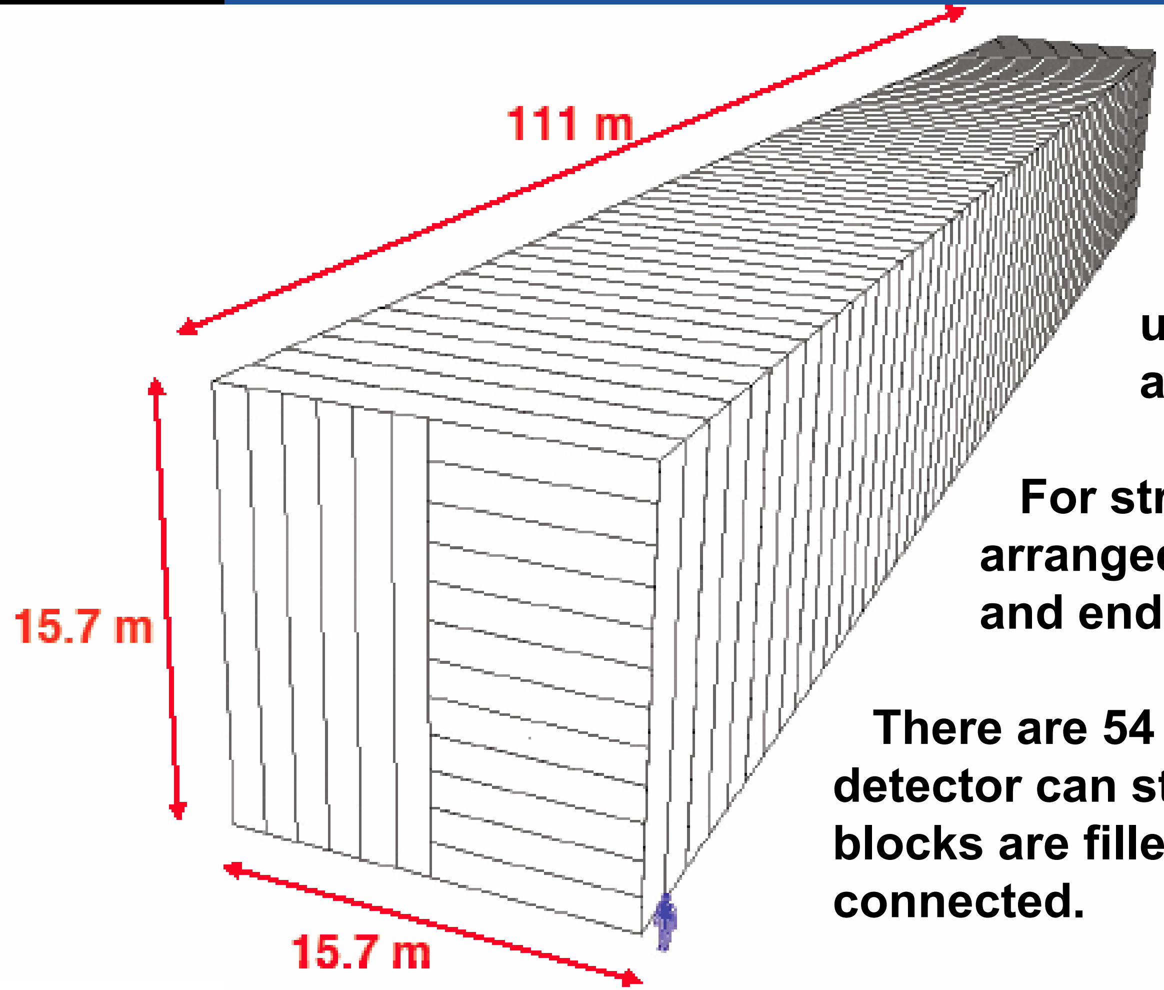


Liquid scintillator in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.

Light is collected in a U-shaped 0.8 mm wavelength-shifting fiber, both ends of which terminate in a pixel of a 32-pixel avalanche photodiode (APD).

The APD has peak quantum efficiency of 85%. It will be run at a gain of 100. It must be cooled to -15^{o}C and requires a very low noise amplifier.

The Far Detector



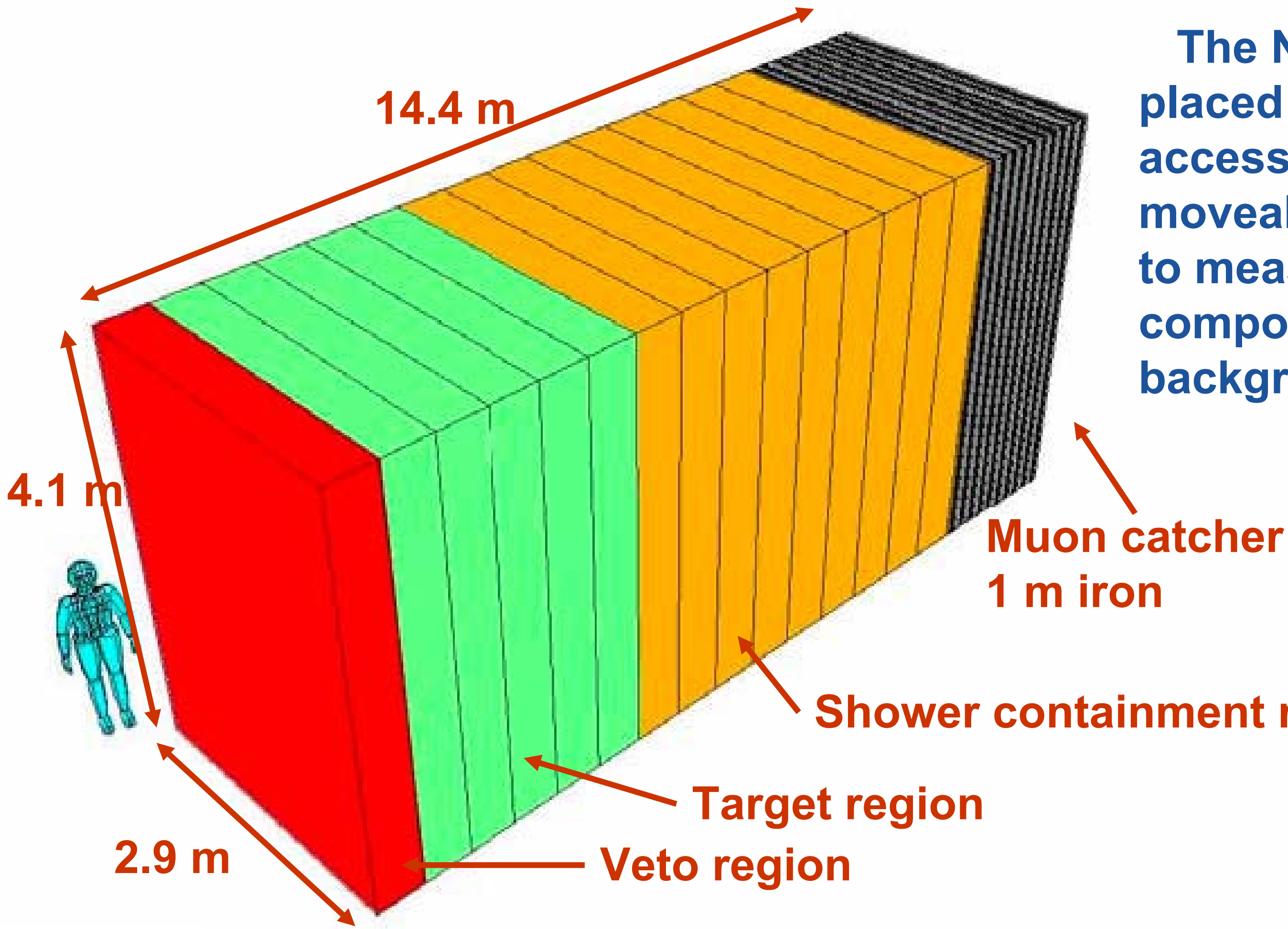
The cells are made from 32-cell extrusions.

12 extrusion modules make up a plane. The planes alternate horizontal and vertical.

For structural reasons, the planes are arranged in 31-plane blocks, beginning and ending in a vertical plane.

There are 54 blocks = 1654 planes. The detector can start taking data as soon as blocks are filled and the electronics connected.

The Near Detector

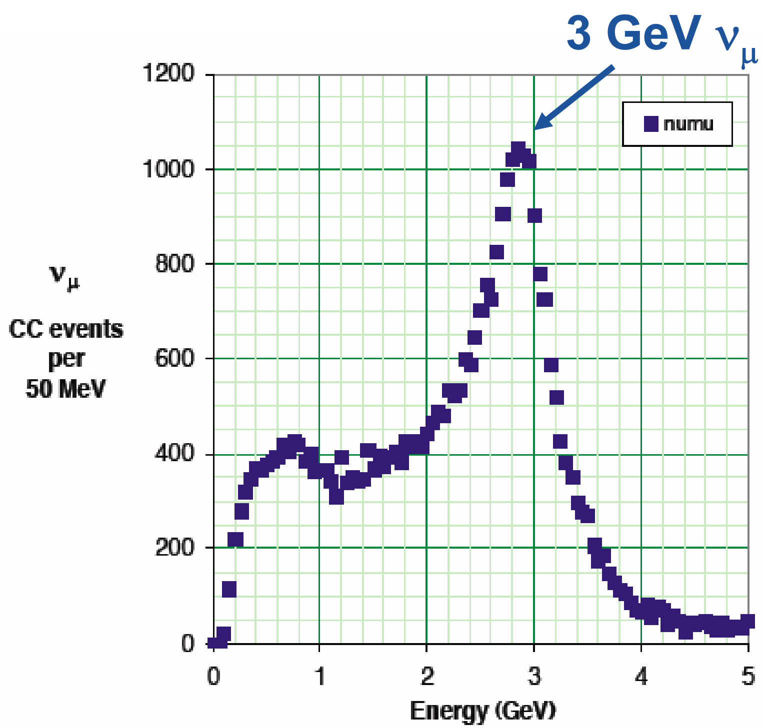


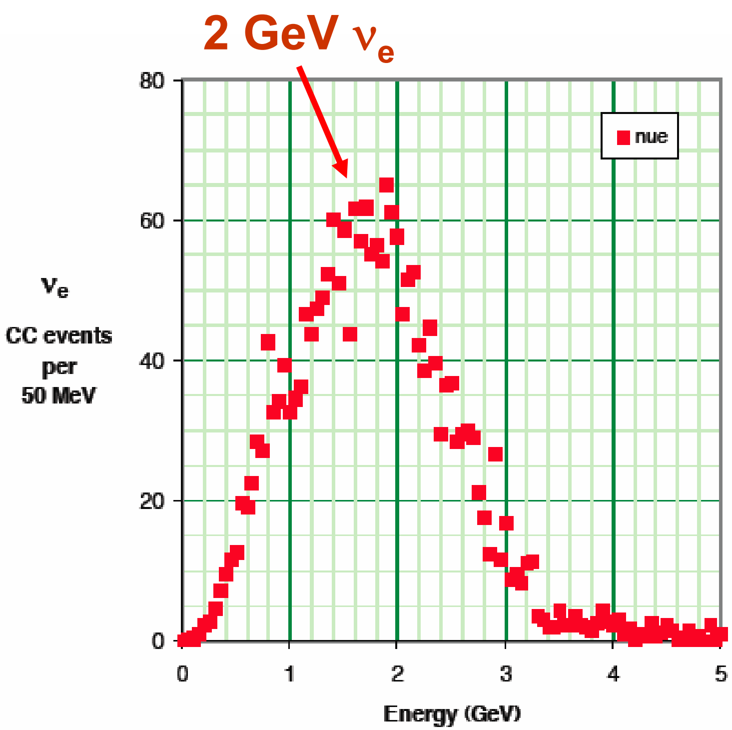
The Near Detector will be placed off-axis in the MINOS access tunnel and will be moveable along the tunnel to measure the different components of the backgrounds.

209 T
126 T totally active
23 T fiducial

The Integration Prototype Near Detector

We plan to have a prototype version of the Near Detector running in the MINOS surface building by the end of 2007.
It will detect a 75 mr off-axis NuMI beam, dominated by *K* decays.

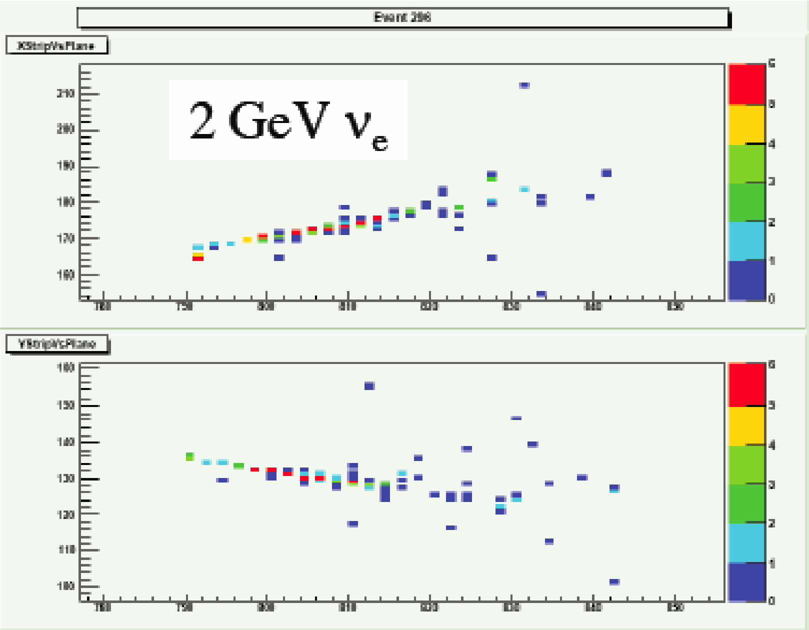


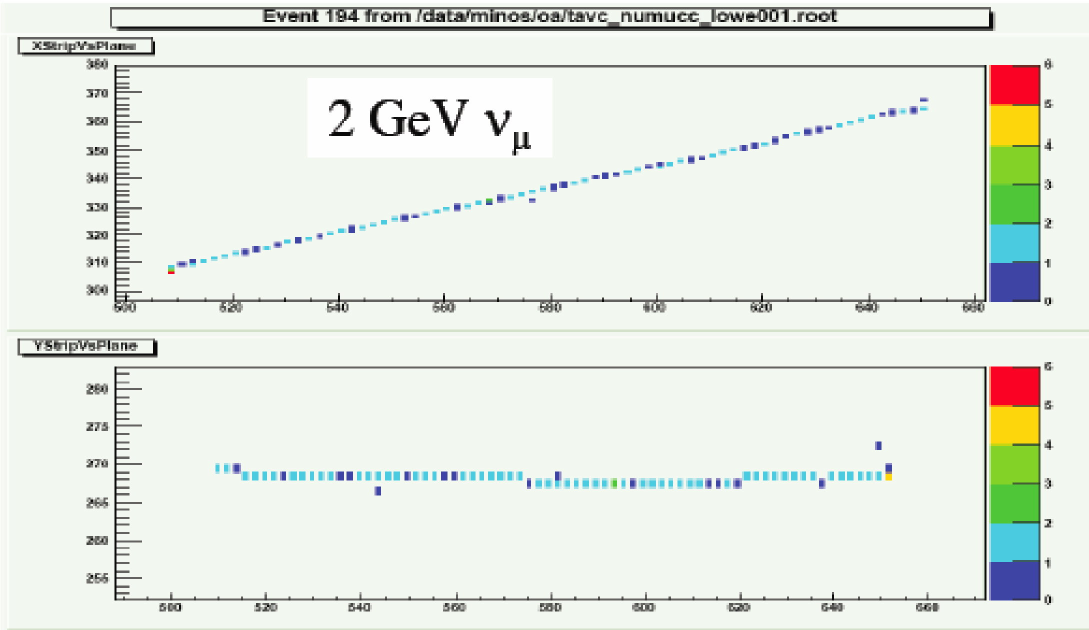


Event Quality

Longitudinal sampling is 0.15 X0, which gives excellent μ-*e* separation.

A 2-GeV muon is 60 planes long.





Neutrino Oscillations

- Neutrino oscillations occur because the weak eigenstates and not identical to the mass eigenstates.
- The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix

- **The mixing matrix can be specified by 3 angles and one complex phase:**

$$\left| \nu_\ell \right\rangle = U \left| \nu_n \right\rangle, \quad \textbf{where} \quad (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{Atmospheric} \\ \nu_\mu \leftrightarrow \nu_\tau}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{Atmospheric} \\ \nu_e \leftrightarrow \nu_\mu,\, \nu_\tau}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Vacuum Oscillations

- **When a 2 x 2 oscillation is sufficient, in vacuum,**

$$i\hbar \frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}, \quad H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

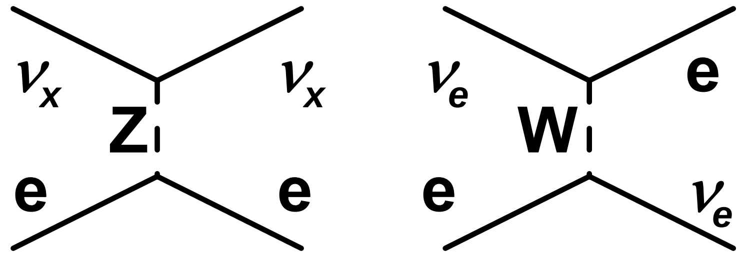
$$P(\nu_e \to \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ is in } (\text{eV}/c^2)^2,$$

L is in km, and E is in GeV

Matter Oscillations

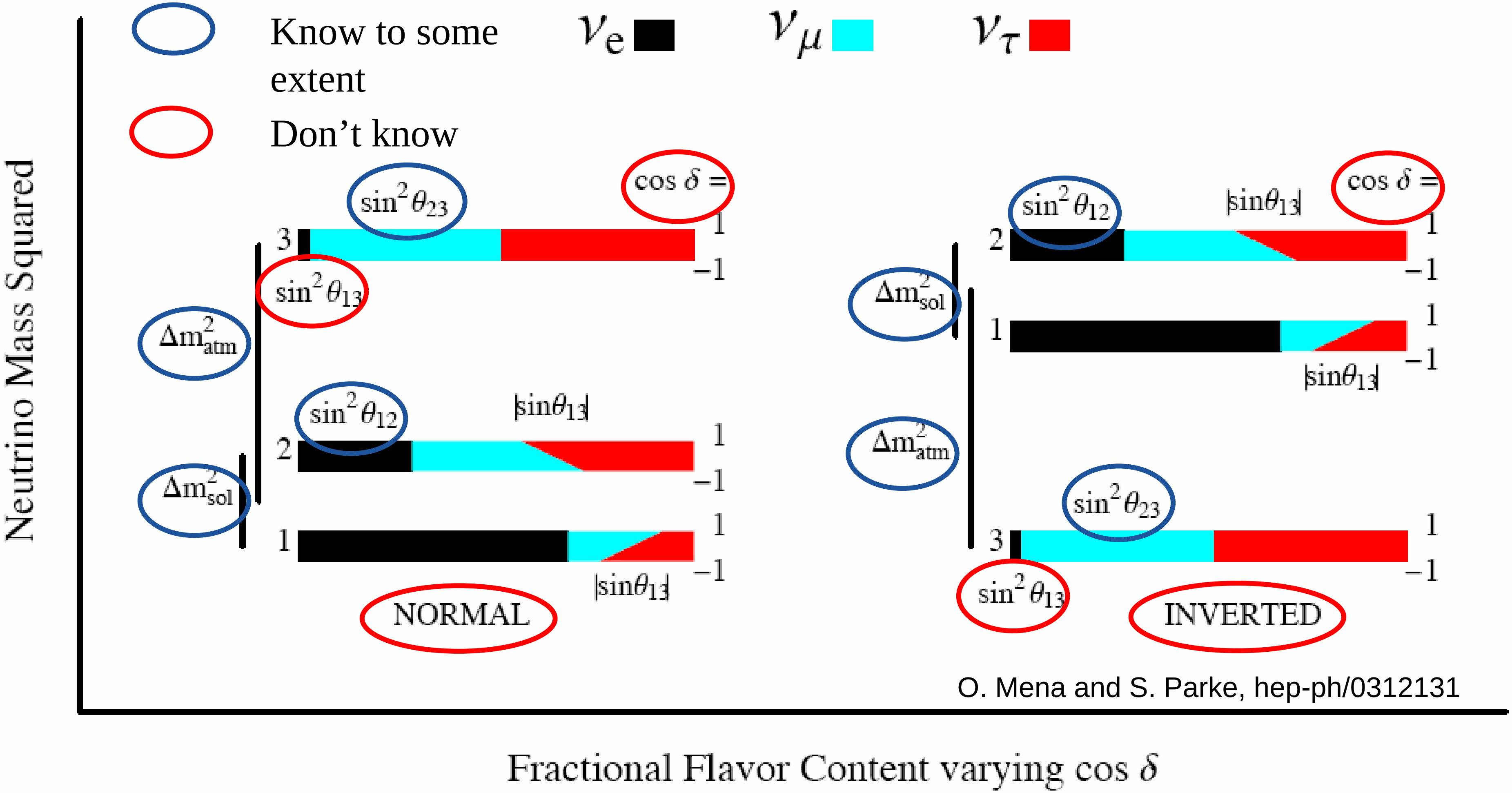
- **Matter effects: In matter ν_e's interact differently than ν_x's.**



$$H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2}G_F\rho_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \sqrt{2}G_F\rho_e E / \Delta m^2)^2 + \sin^2 2\theta}$$

What We Know and What We Don't Know



$P(\nu_\mu \to \nu_e)$ (in Vacuum)

- $P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  Atmospheric-solar interference

  where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})\ \times$

  $$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$$

$P(\nu_\mu \to \nu_e)$
(in Matter)

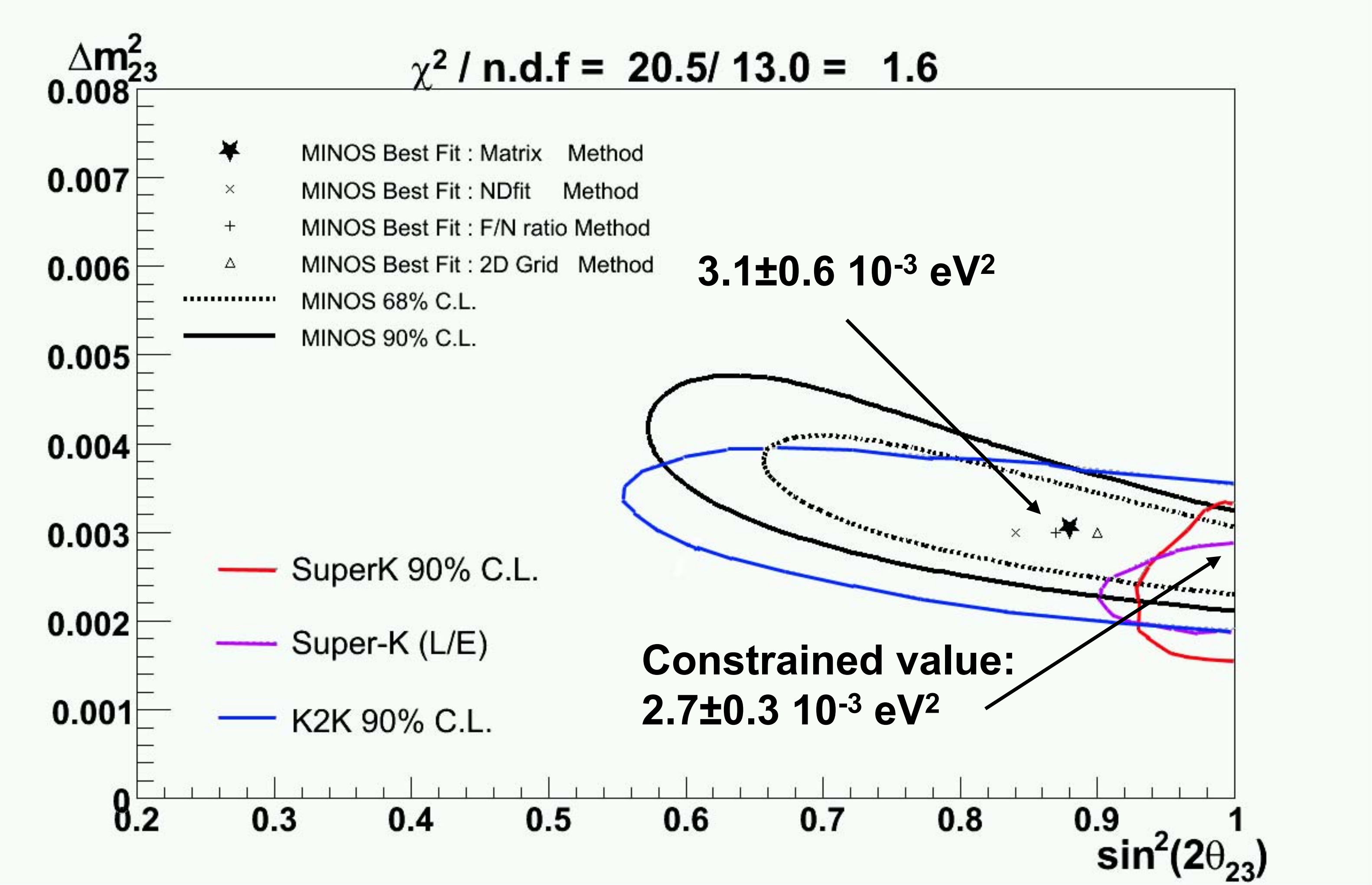
- In matter **at oscillation maximum**, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F \rho_e} \approx 11\ \text{GeV for the earthÕs crust.}$$

About a ±30% effect for NuMI, but only a ±11% effect for T2K.

However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

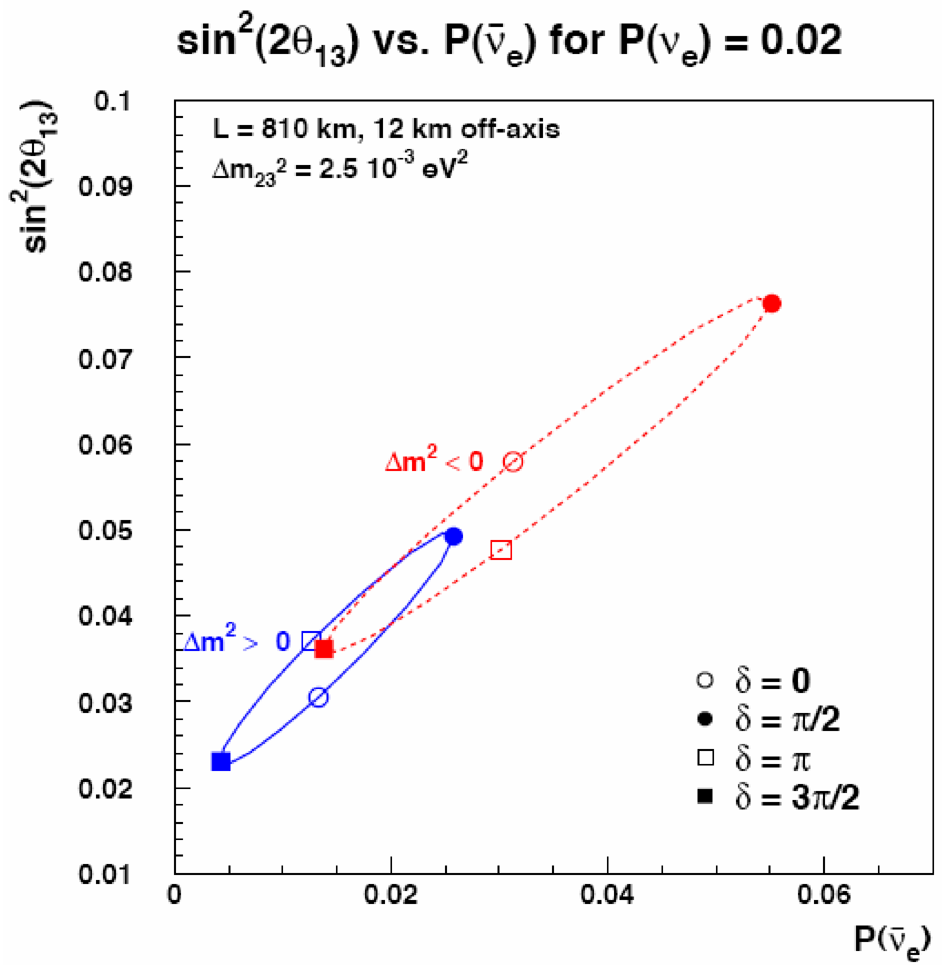
Recent MINOS Measurement



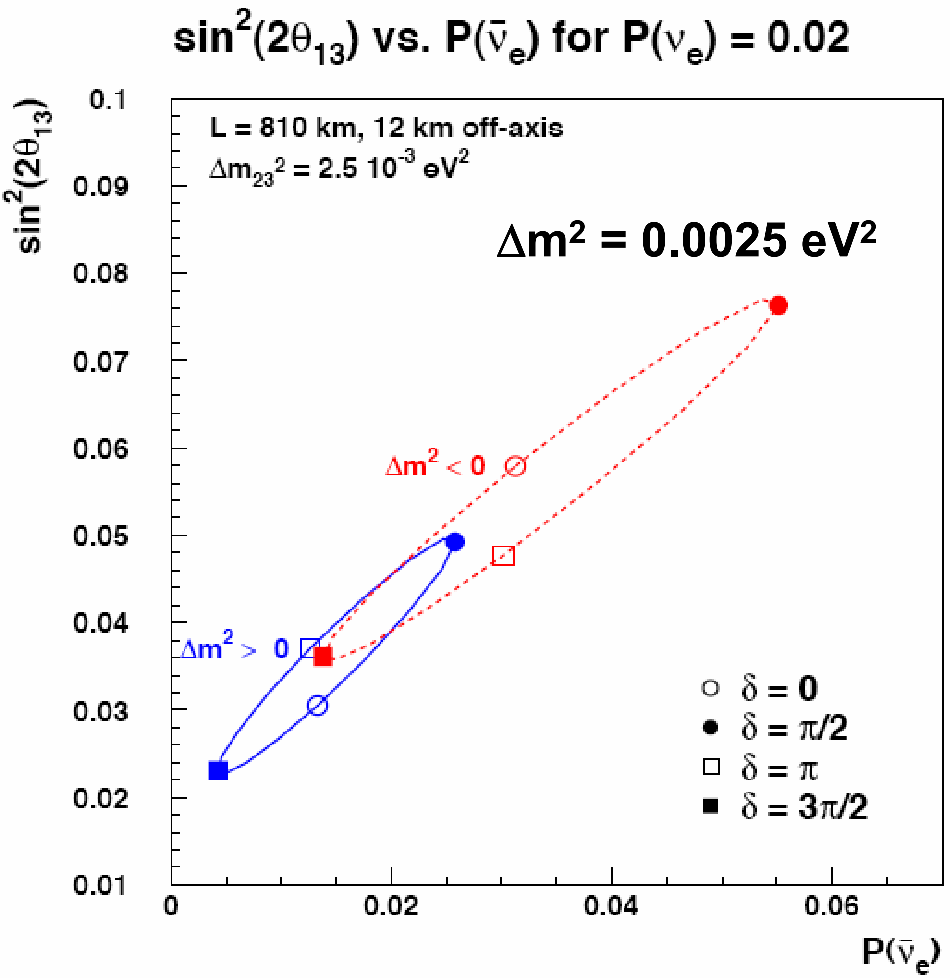
Status of Δm_{32}^2

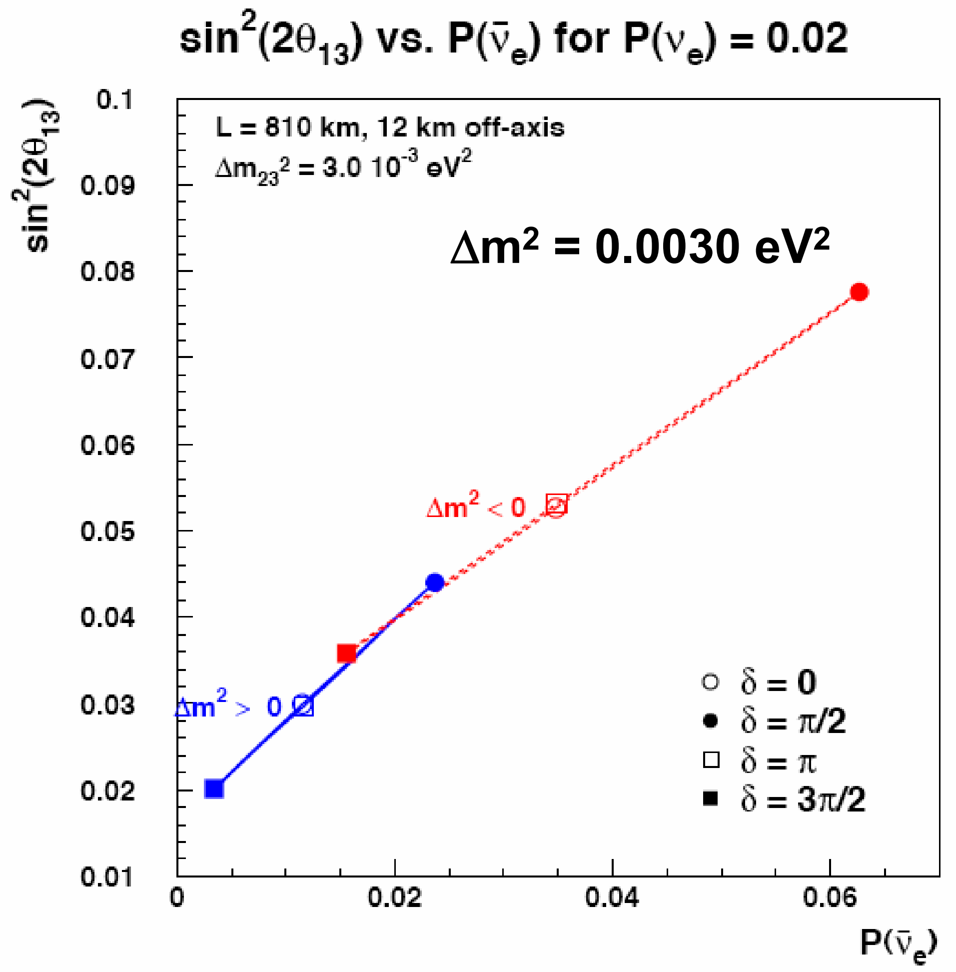
- The best measurement of $\sin^2(2\theta_{23})$ is from SuperK, and the best value is 1.0.
- The single best measurement of Δm_{32}^2 is now from MINOS and it is $(2.7\pm0.3)\ 10^{-3}\ \mathrm{eV}^2$, when it is constrained to $\sin^2(2\theta_{23}) = 1$.
- The K2K central value of $\Delta m_{32}^2 = 2.8\ 10^{-3}\ \mathrm{eV}^2$ and SuperK *L*/*E* central value of $\Delta m_{32}^2 = 2.4\ 10^{-3}\ \mathrm{eV}^2$ are in good agreement with the MINOS value.
- Therefore, I will show calculations at Δm_{32}^2 of both 2.5 and 3.0 eV^2, roughly the $\pm\ 1\sigma$ values for our present knowledge.

Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation



Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation





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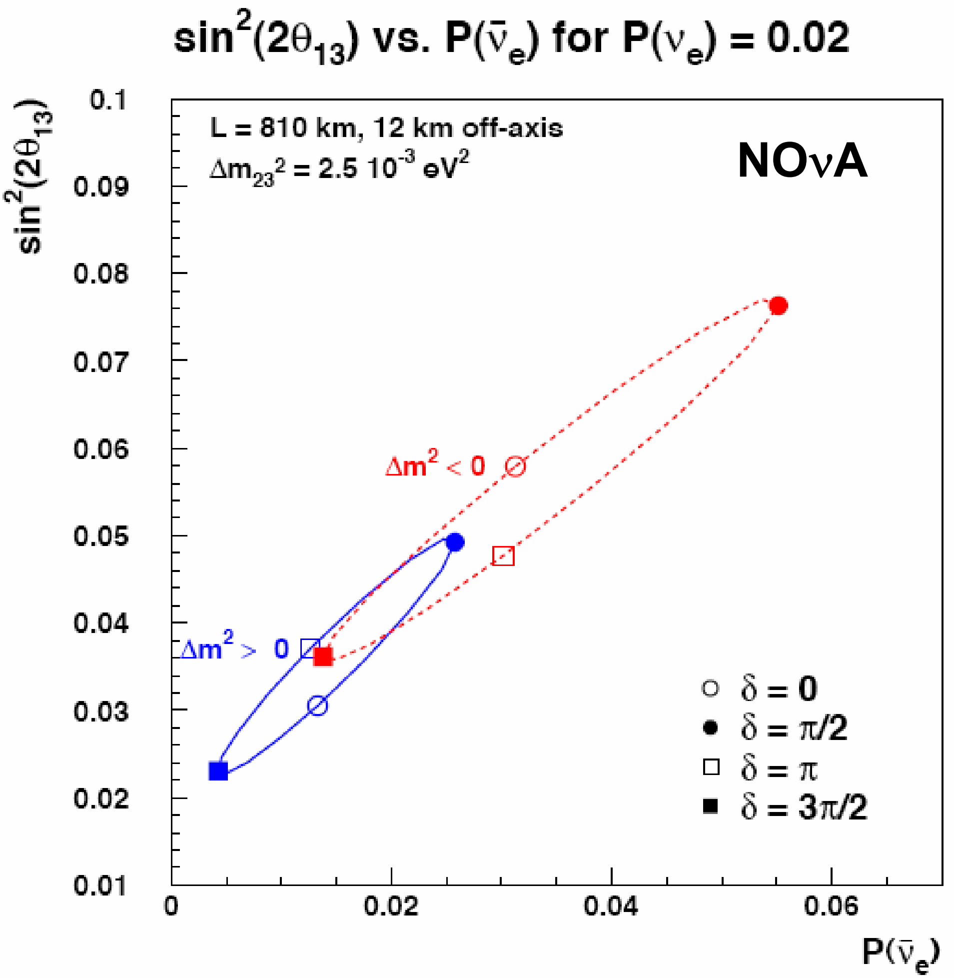
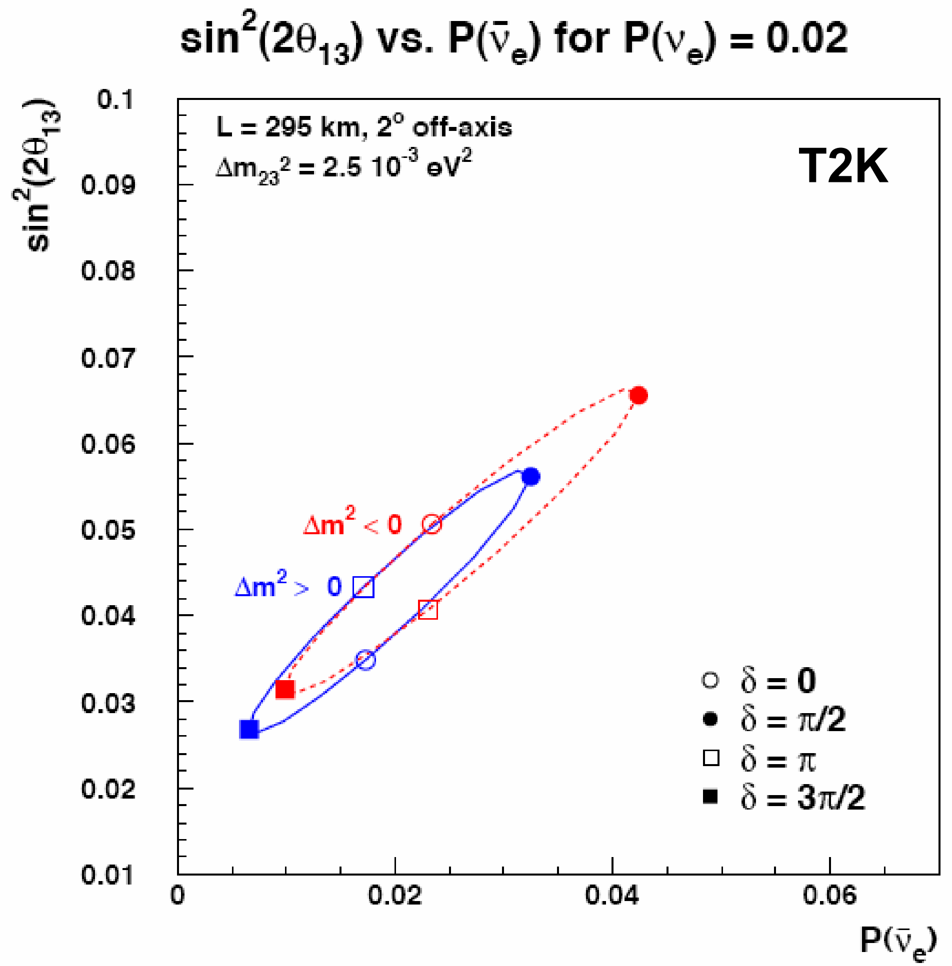
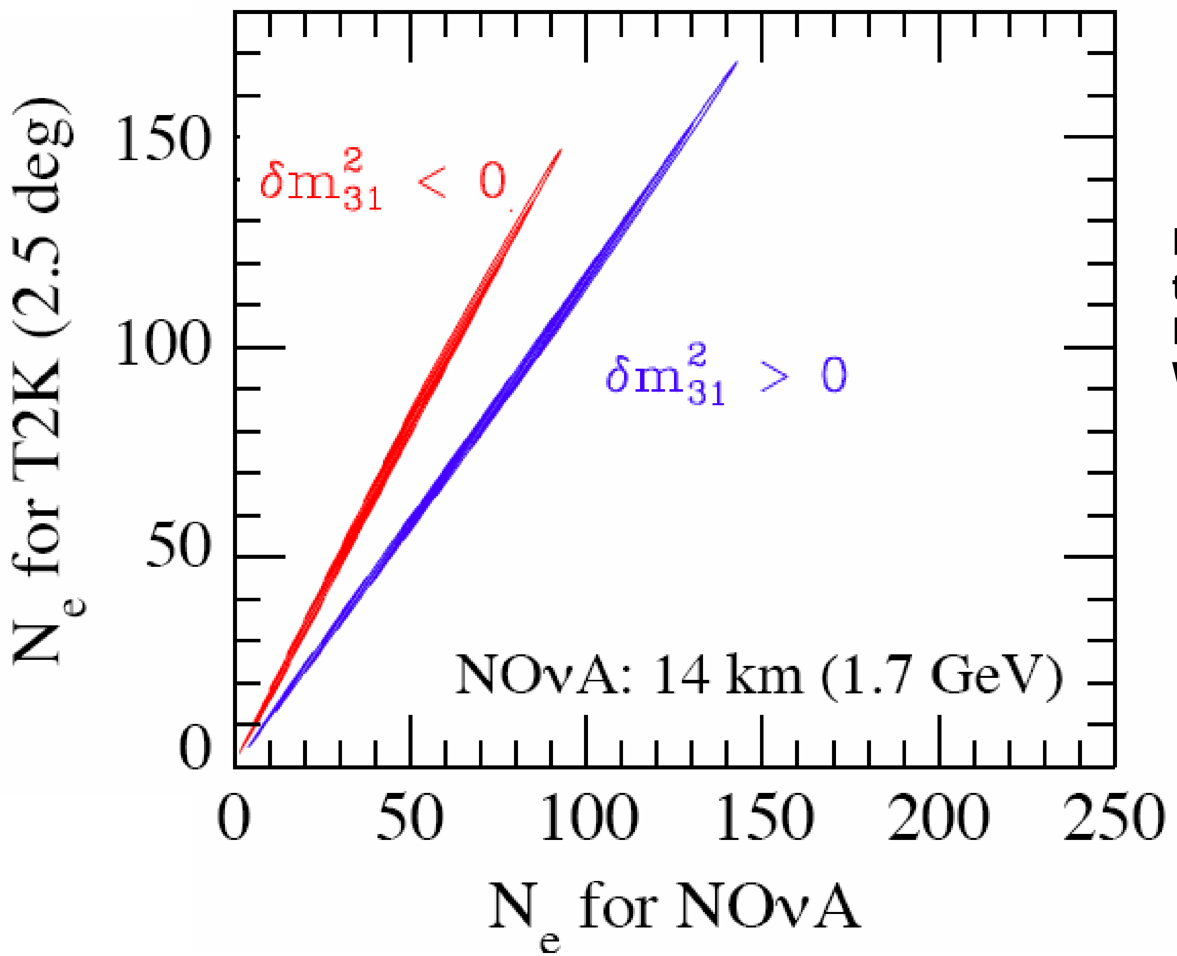


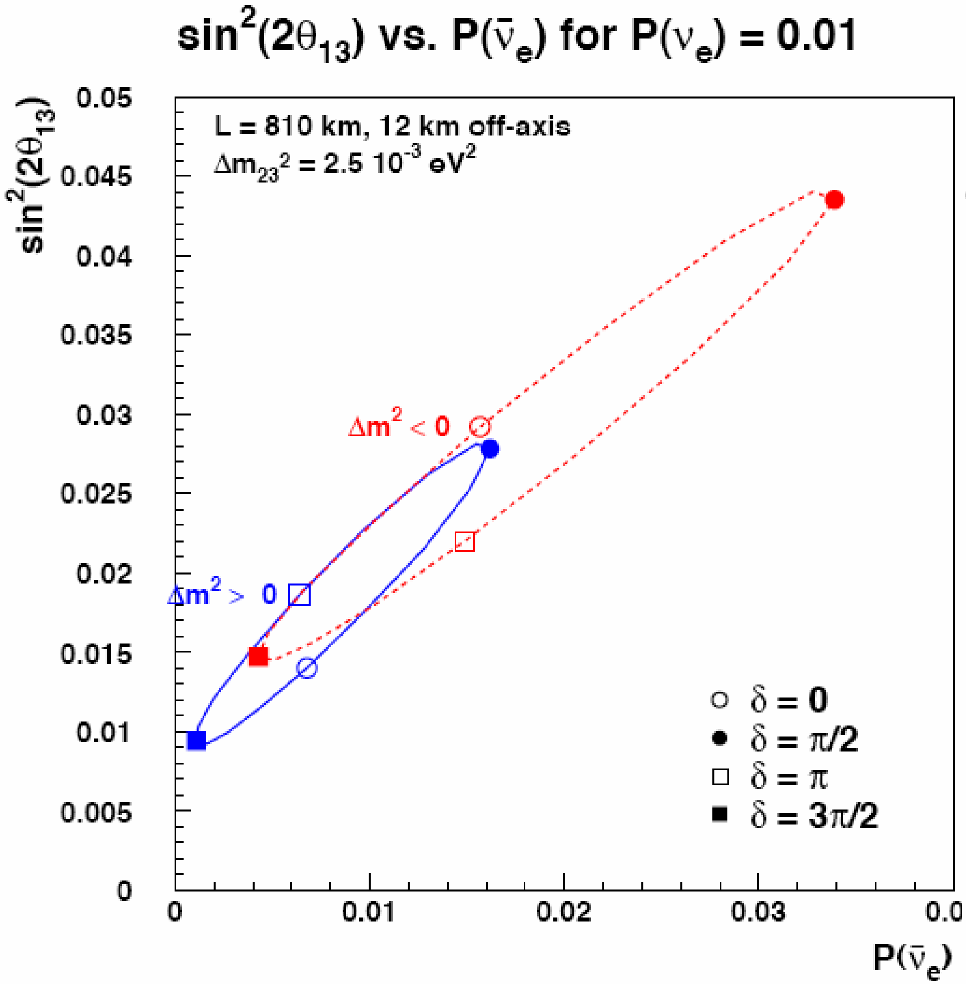


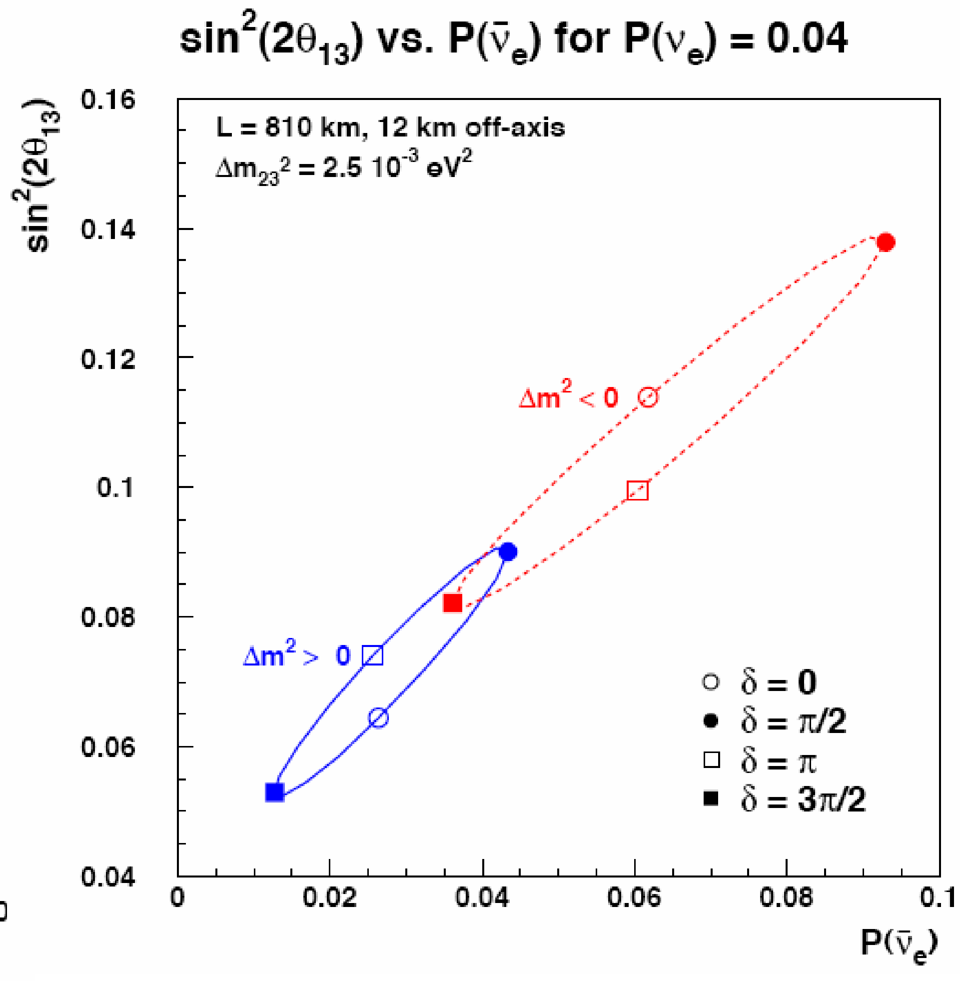
T2K-NOνA Comparison



From O. Mena talk at BNL-FNAL Workshop

Parameters Consistent with a 1% or 4% $\nu_\mu \rightarrow \nu_e$ Oscillation





Simulations

- The physics projections are based on a full reconstruction:
  - Raw hits are produce by a Monte Carlo simulation.
  - The hits are reconstructed into physics objects.
  - A likelihood function is constructed to separate ν_e events from backgrounds.
  - A cut on the likelihood function is made to maximize a figure of merit (FoM) = signal$/\sqrt{\text{background}}$.
- Last summer, two blind hand scans obtained FoM's that were 22% and 28% better than the program. The scanners concluded that the lower performance of the program was due to reconstruction errors.

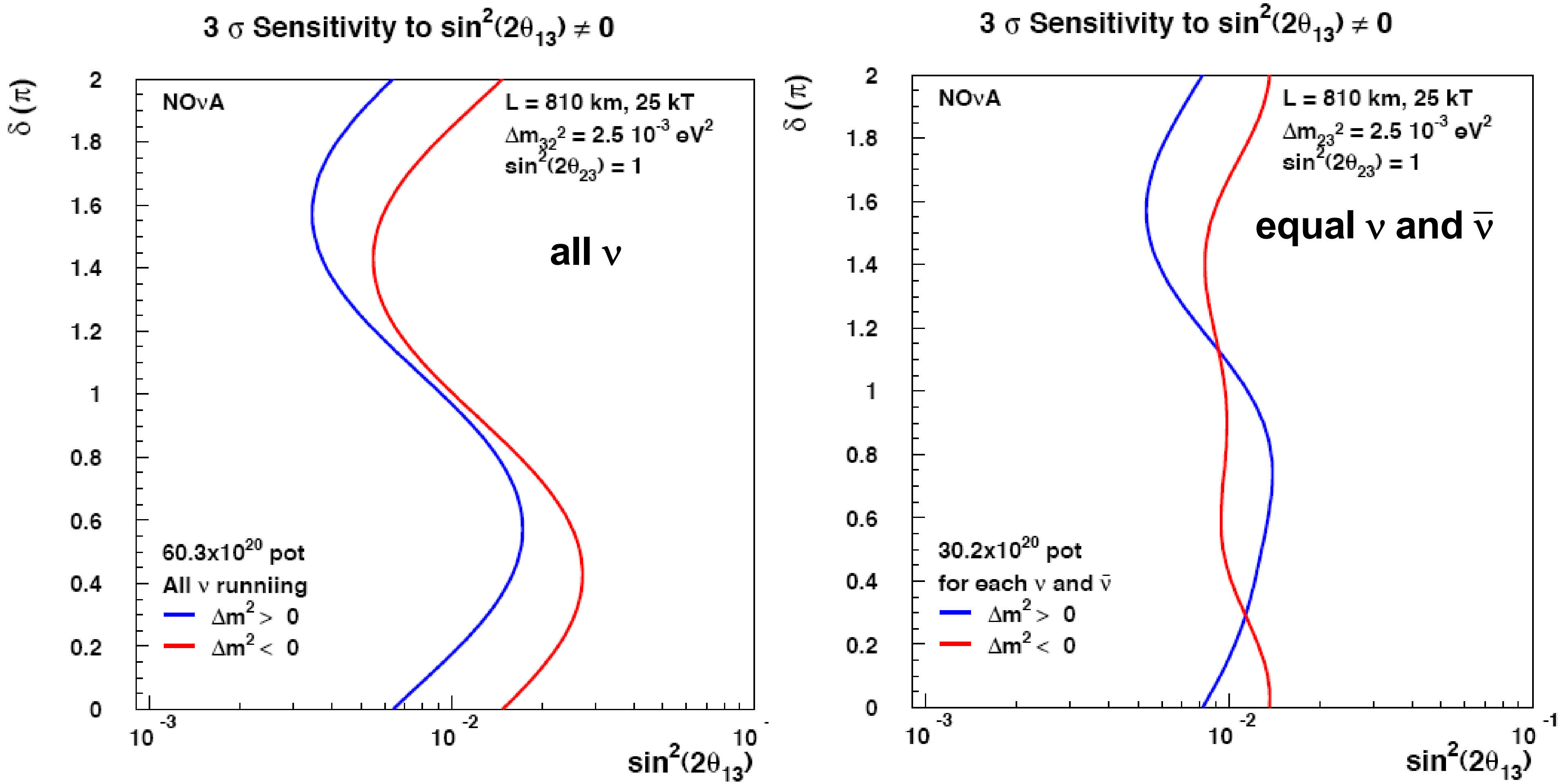
Proton Plan

- The physics projections are also based on the proton plan that Pier discussed this morning.
  - FY2010: Full year down period to convert the Main Injector to a 1 MW proton source
    - Conversion of the Recycler and Accumulator into proton stackers
    - Construction of Booster-Accumulator and Accumulator-Recycler transfer lines
    - Main Injector rf upgrade
    - NuMI target upgrade
  - FY2011: 44 weeks of running; 400 kW to 700 kW
  - FY2012: 38 weeks of running; 700 kW to 1 MW
  - FY2013 and beyond: 44 weeks of running at 1 MW

Proton Plan

- Degradation factors assumed:
  - Accelerator uptime: 85%
  - Average to peak: 90%
  - NuMI uptime: 90%
  - $\Rightarrow$ overall efficiency: 69%
- Assumed that NOνA would begin running when 5 kT had been commissioned and would run for 6 years from the end of construction, giving a total of 60.3 10^{20} pot.

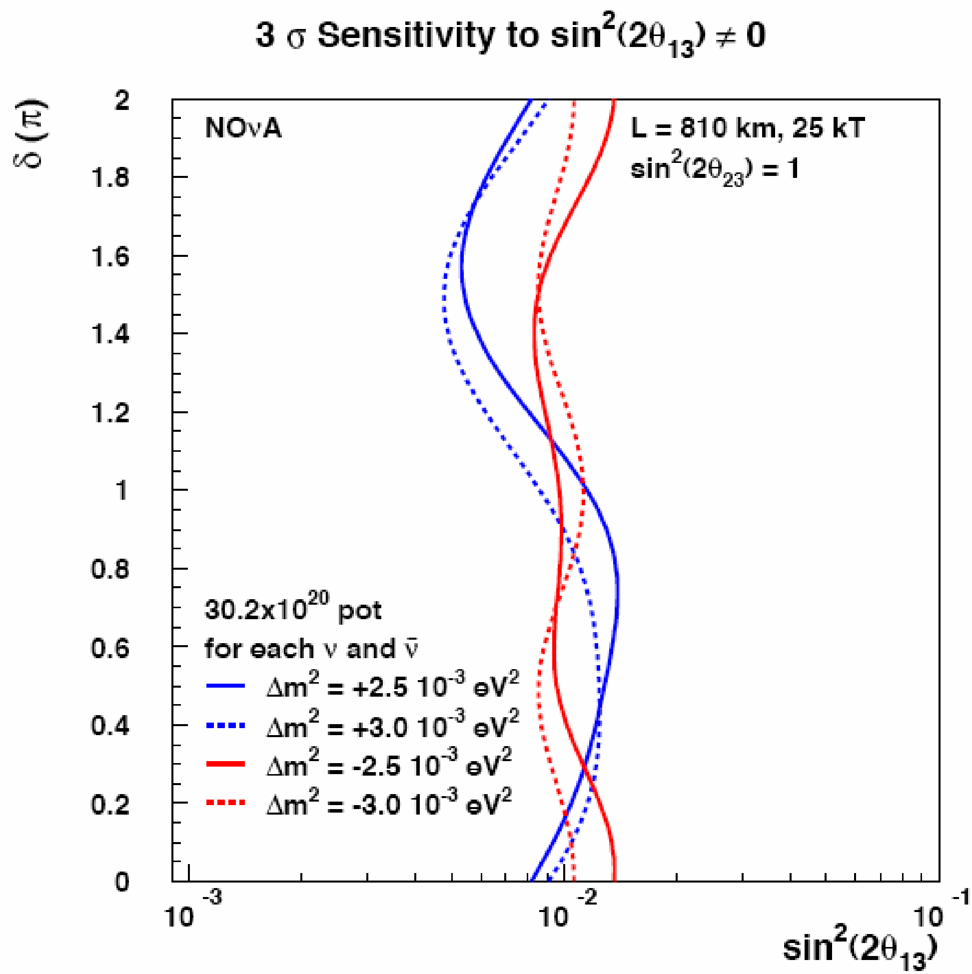
3 σ Sensitivity to $\theta_{13} \neq 0$



Assumed Running Plan

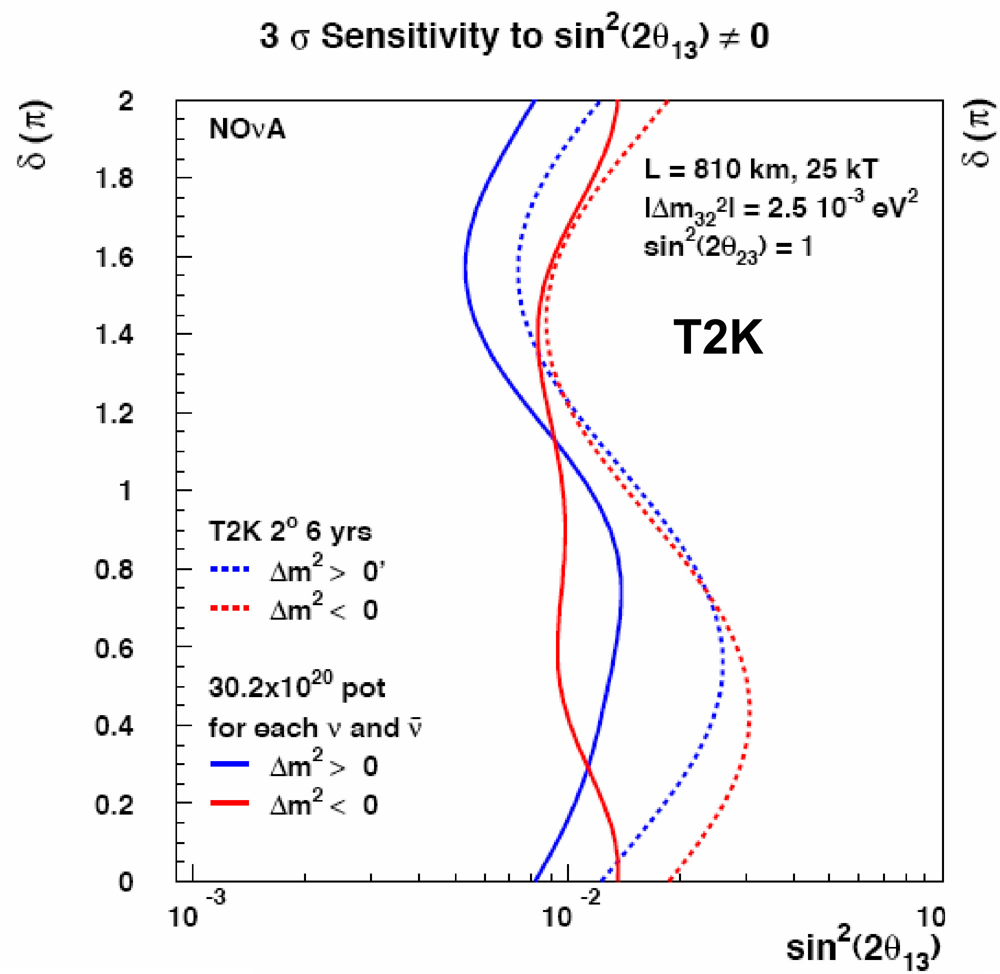
- Although this is clearly a decision that will be made on the fly as physics unfolds, I will assume that NOνA will run equal time on neutrinos and antineutrinos.
  - Flatter response in the mass ordering and δ_{CP}
  - When a signal is seen, it gives information on the mass ordering and δ_{CP}
  - Better complementarity with T2K if it runs only neutrinos
- For the timeline, to be shown later, we will assume that the first 3 years are neutrino running and the last 3 years are antineutrino running.

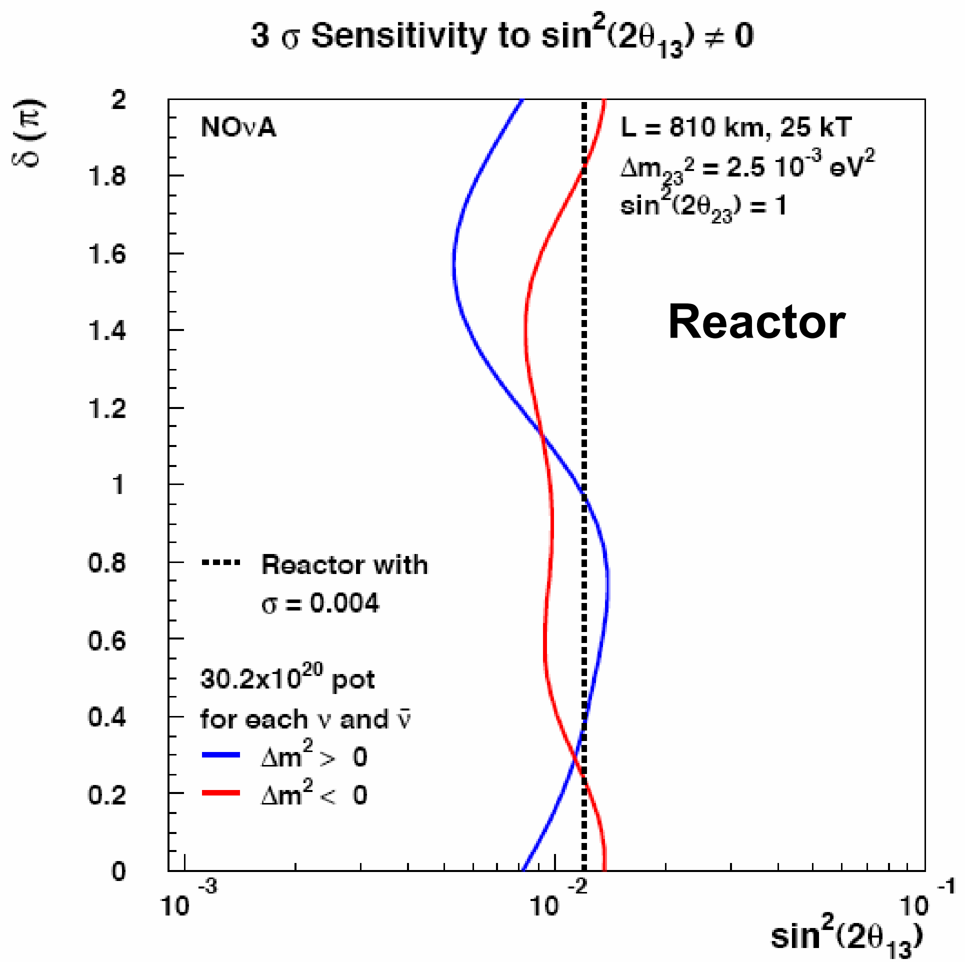
Comparison of $\Delta m^2 = 0.0025$ and $0.0030\ eV^2$



Not a great deal of difference

Comparison to T2K and a Reactor Experiment

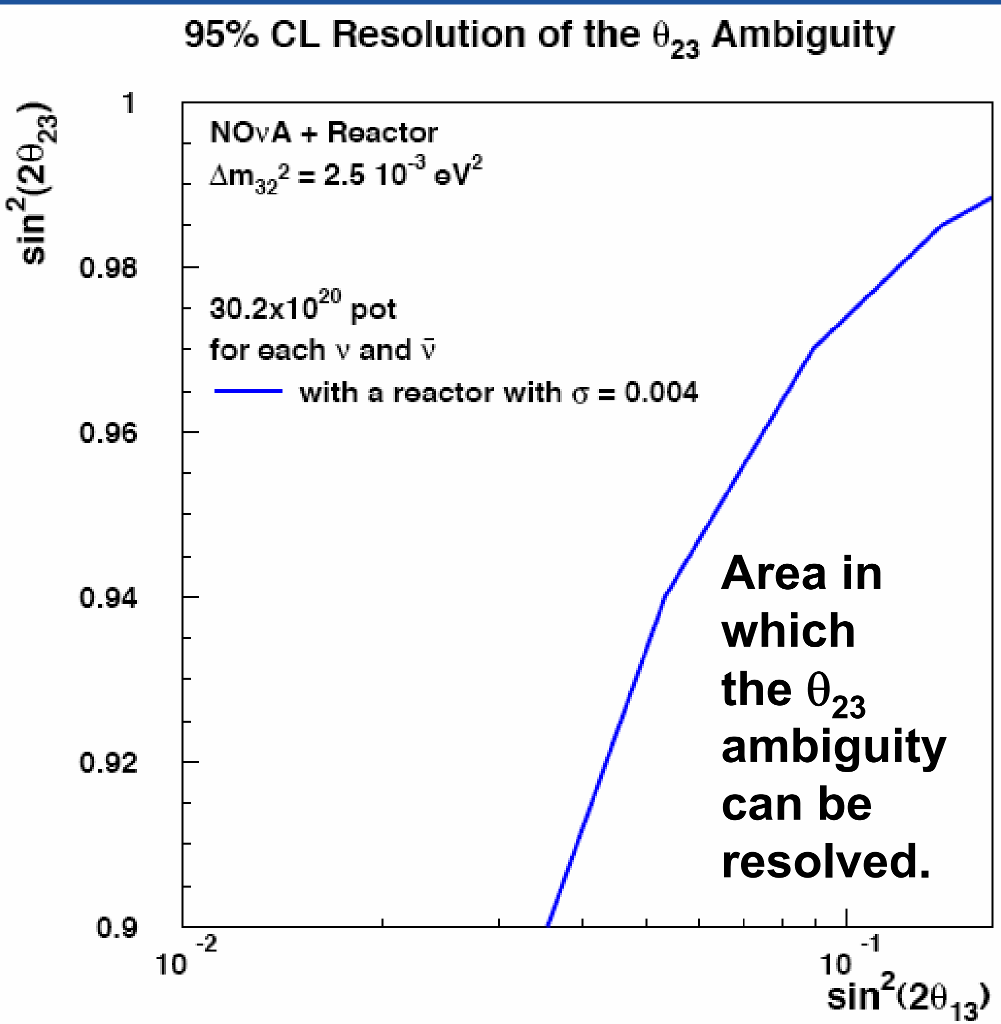




Comment

- There will be an ambiguity in comparing accelerator and reactor experiments if the θ_{23} mixing is not maximal.
  - Reactor experiments are sensitive to $\sin^2(2\theta_{13})$.
  - Accelerator experiments are largely sensitive to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$.
  - This is the difference between $\nu_e \leftrightarrow \nu_\mu$ mixing (accelerators) and $\nu_e \leftrightarrow (\nu_\mu + \nu_\tau)$ mixing (reactors).
- Resolving this ambiguity is the main complementarity between the two types of experiments. It can be done if the θ_{23} mixing is sufficiently non-maximal and $\sin^2(2\theta_{13})$ is sufficiently large. (See next slide.)

95% CL Resolution of the θ_{23} Ambiguity

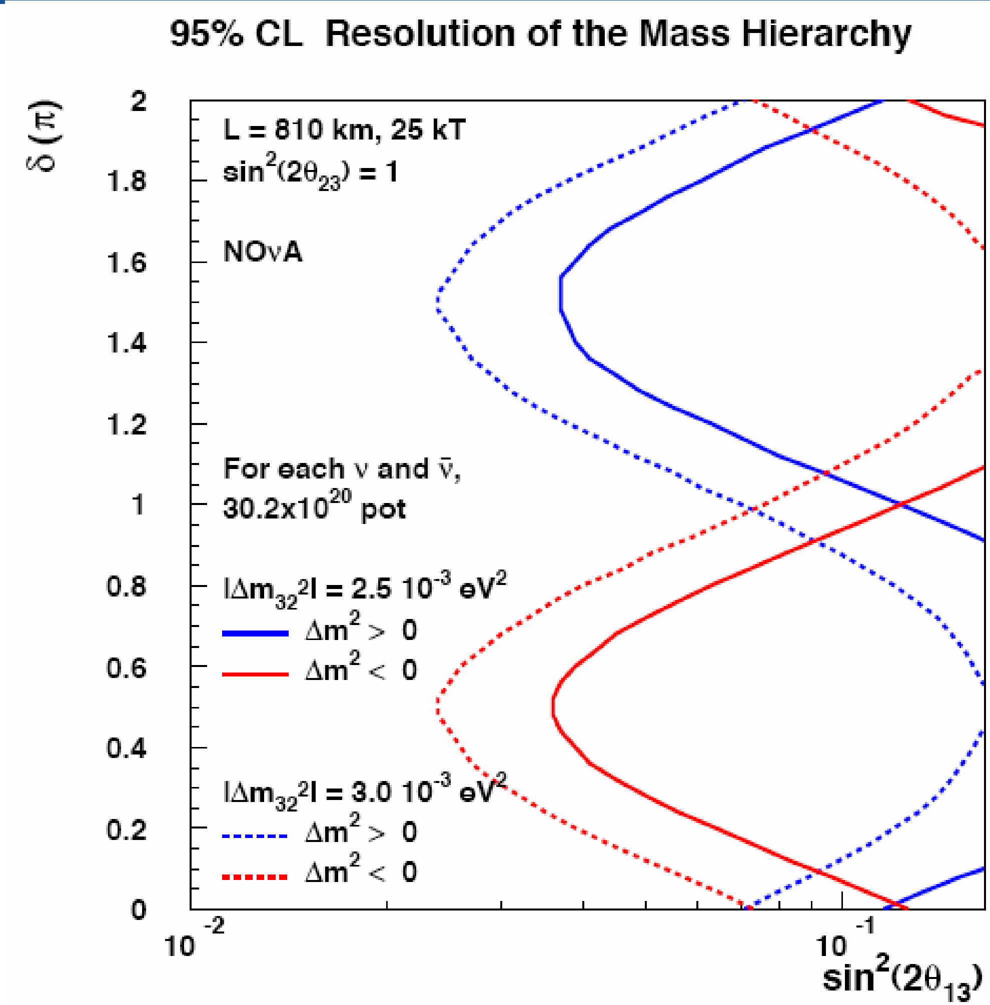


(There is some sensitivity to the mass ordering and δ. The blue line represents an average over these parameters.)

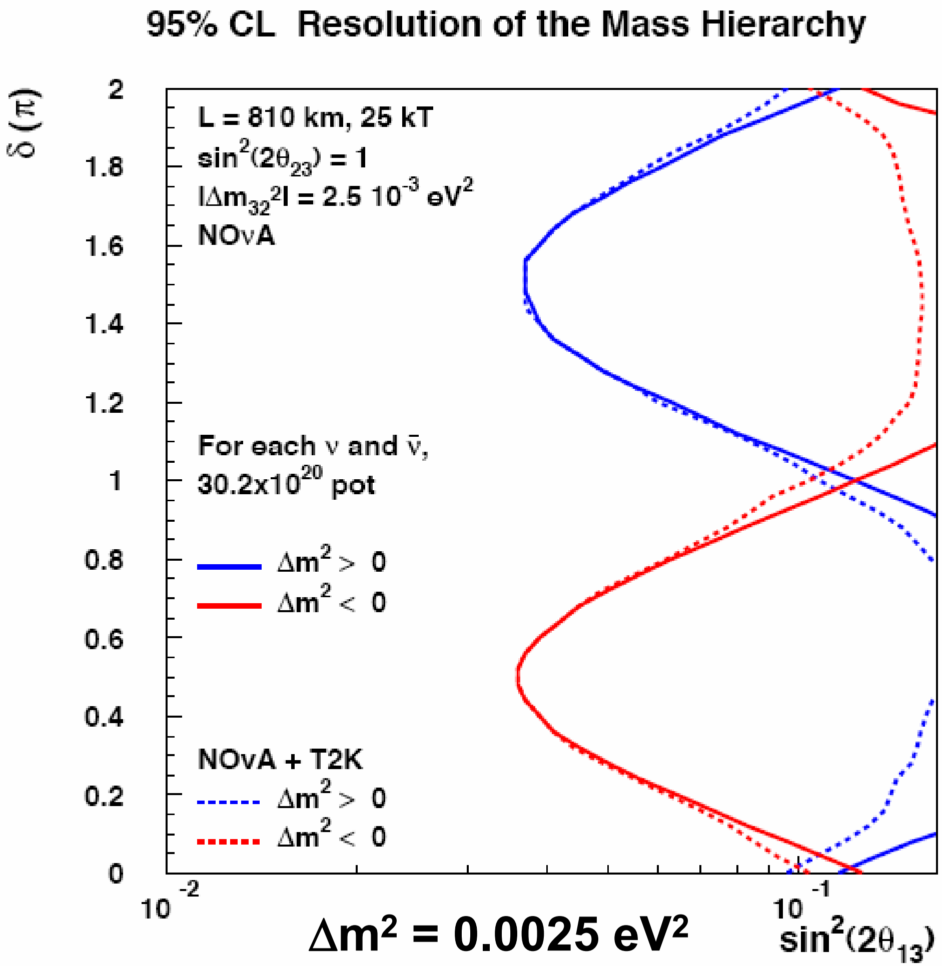
Importance of the Mass Ordering

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

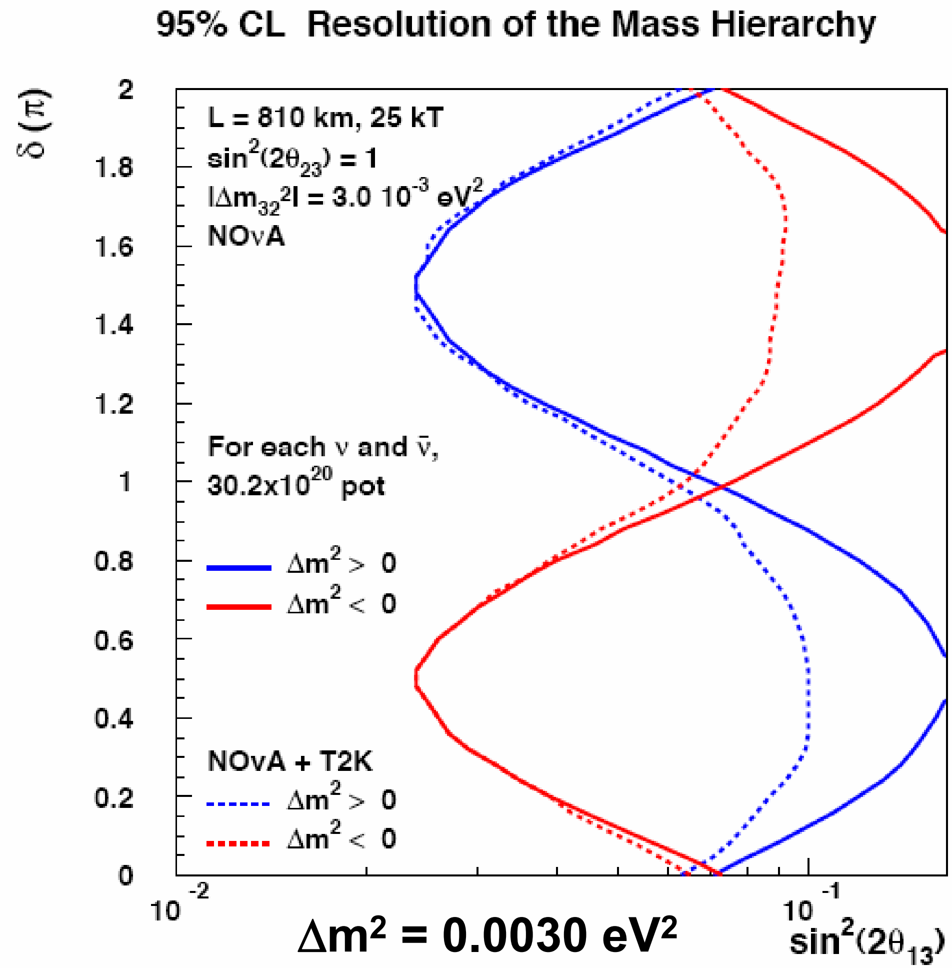
95% CL Resolution of the Mass Ordering



Combining NOνA and T2K



$\Delta m^2 = 0.0025\ eV^2$

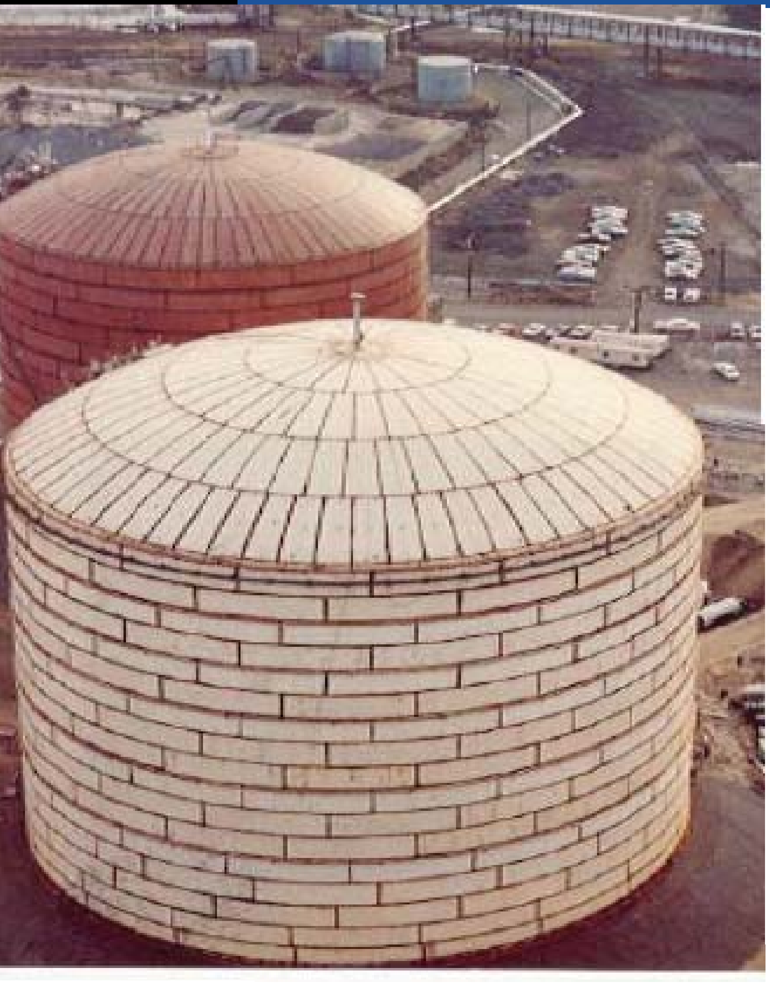


$\Delta m^2 = 0.0030\ eV^2$

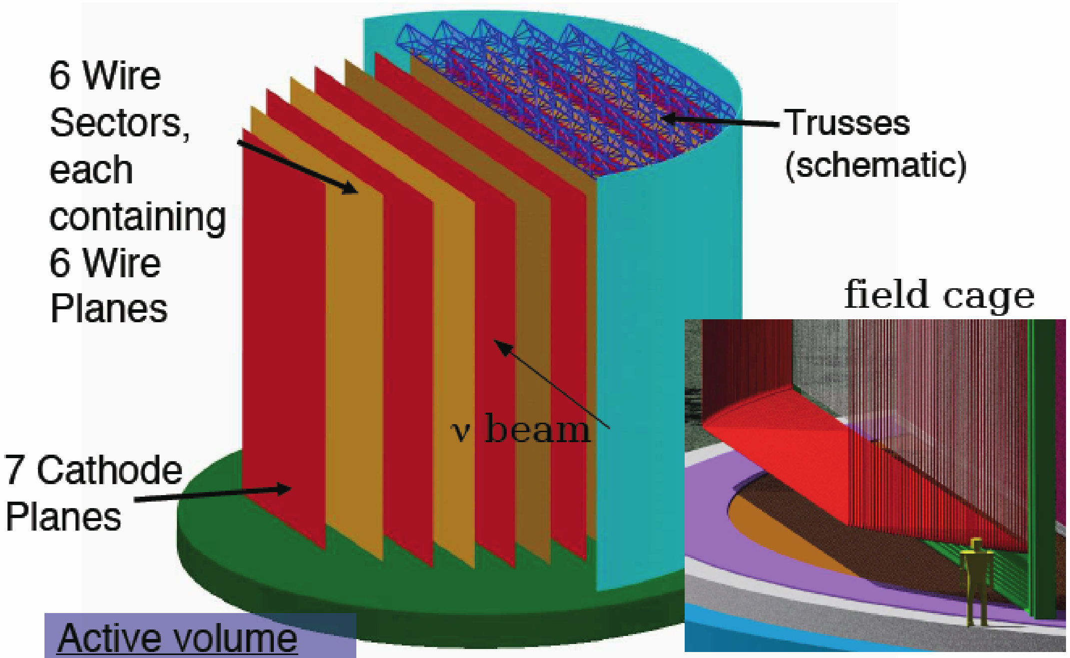
Future Directions

- For the most part I want to focus this talk on the physics of the NOνA proposal as it is.
  - Both a BNL-Fermilab workshop and the new NuSAG charge are evaluating post-NOνA directions, such various additions on the NuMI beamline, or a massive detector at an underground laboratory.
- However, there is a group at Fermilab and several universities working on massive liquid argon TPC detectors. They wanted to speak here, but Abe suggested that I might say a few words about their work instead.

The Idea Is to Use LNG Storage Technology



Modularized drift regions inside tank



Active volume
Diameter: 40m
Height: 30m

Scalable → 15-50 kTons
4 - 6 wire planes

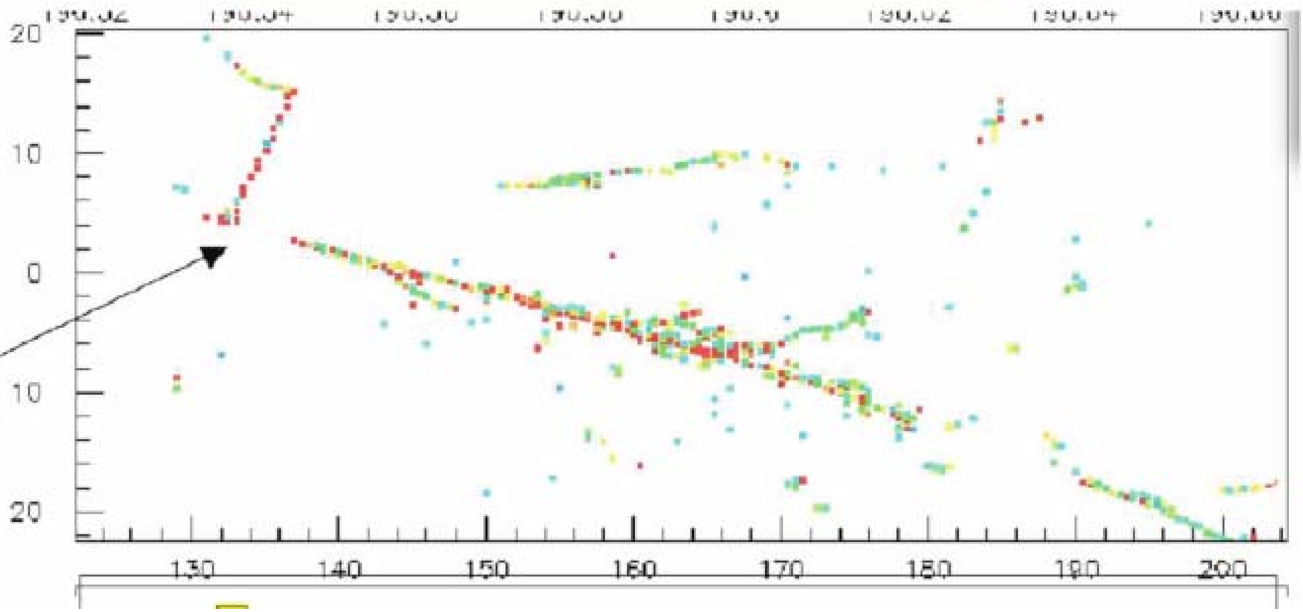
Excellent Pattern Recognition and Resolution

$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples in all 3 views

4 cm gap



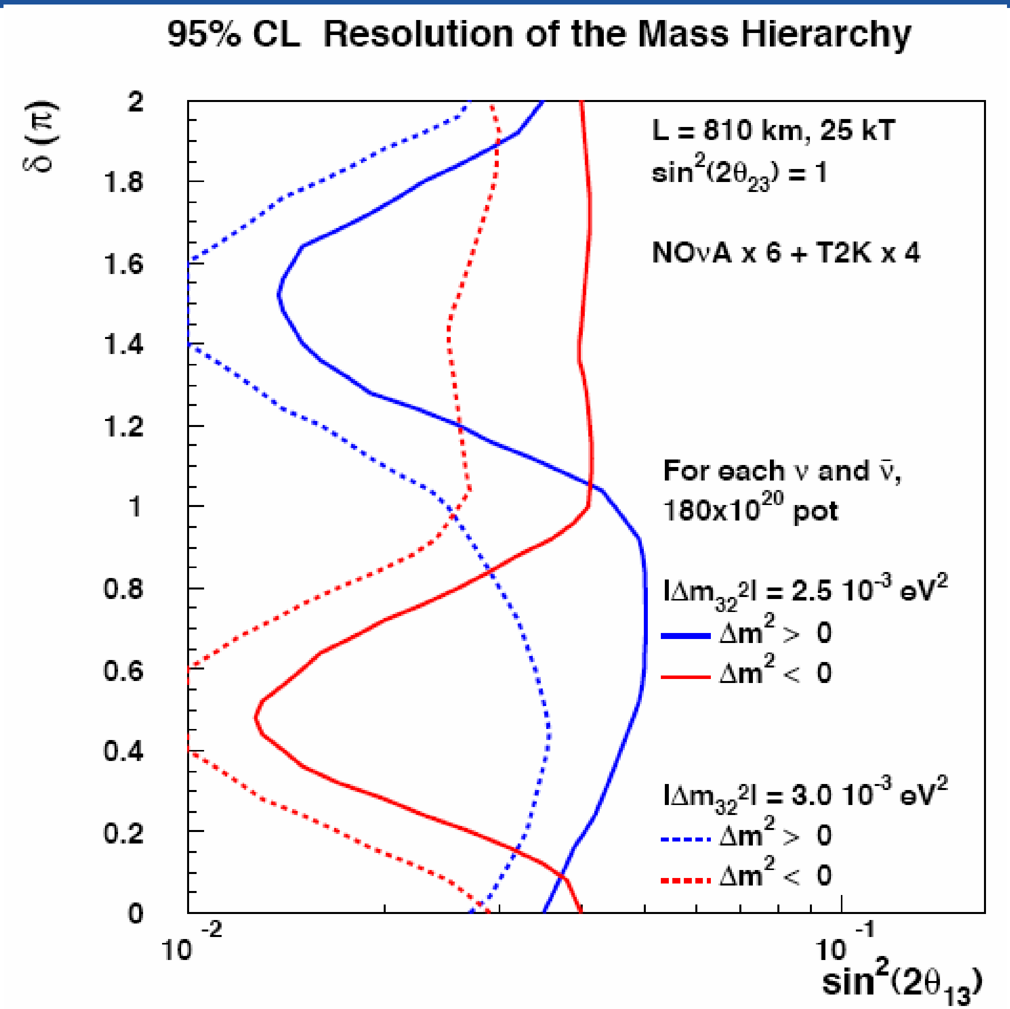
High Efficiency and Low Backgrounds

- **A blind scan of Monte Carlo events gave an 81% efficiency with sufficient neutral current rejection to get below 1/2 the intrinsic beam ν_e background.**

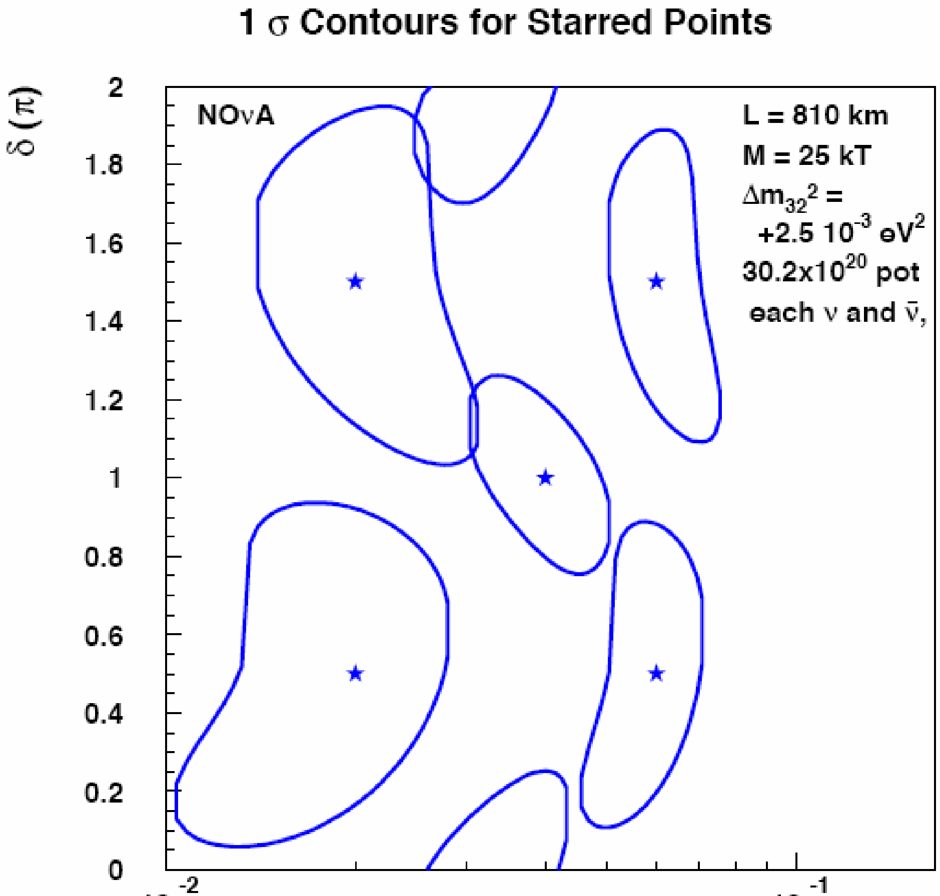
A Possible NOνA II Proposal

- Assume a NOνA-size LA detector, which would be the equivalent of 4 NOνA detectors. Add past and future NOνA runs to make an equivalent total of 6 NOνA detectors running for 6 years.
- Assume that T2K upgrades its proton source by a factor of 4.

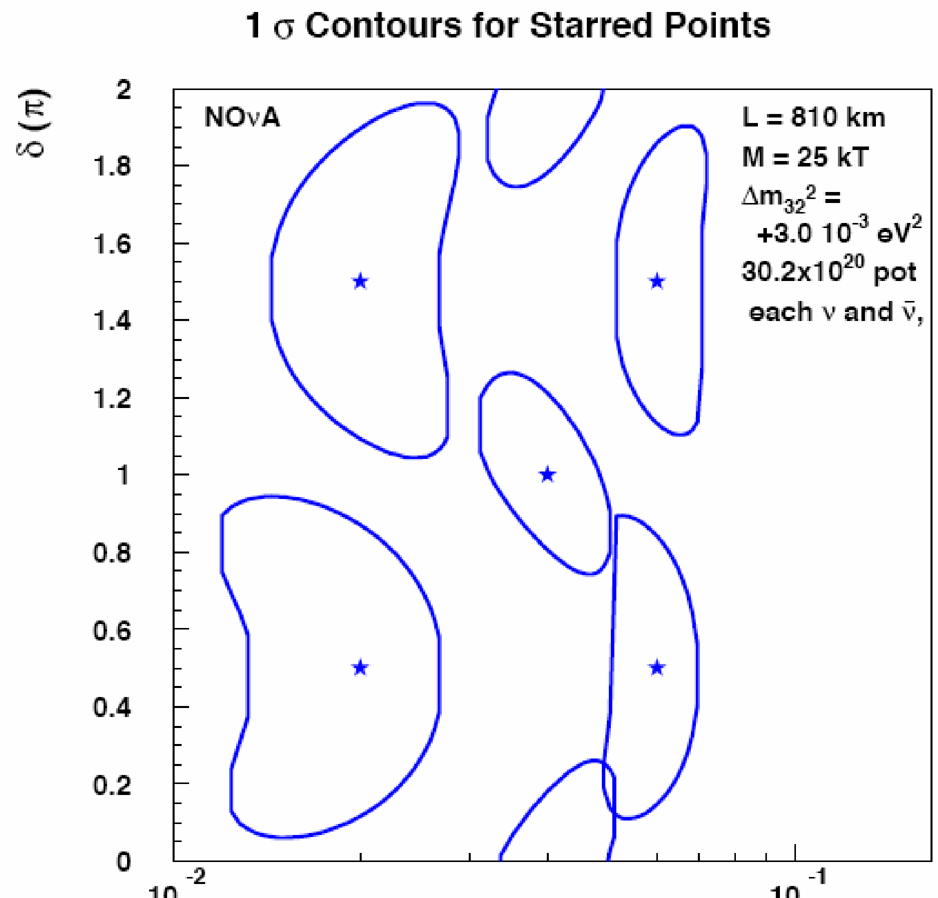
Combining NOνA II with T2K II



Back to NOνA: δ vs. $\sin^2(2\theta_{13})$ Contours

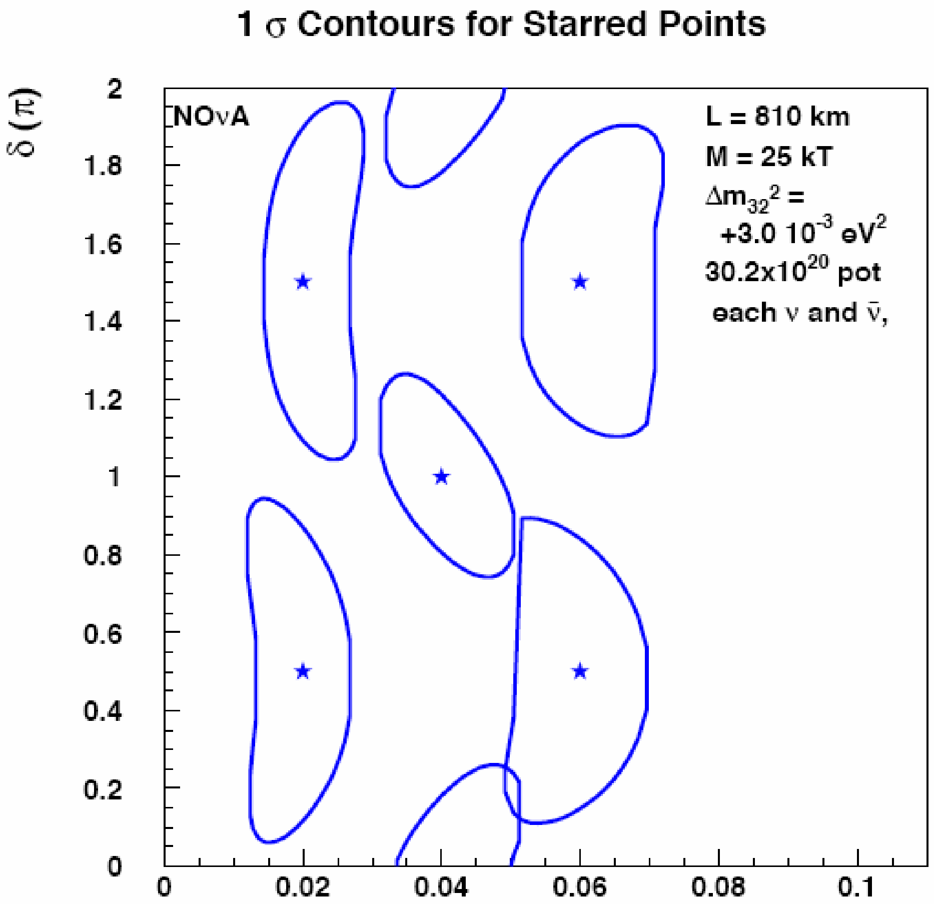


Δm^2 = 0.0025 eV^2

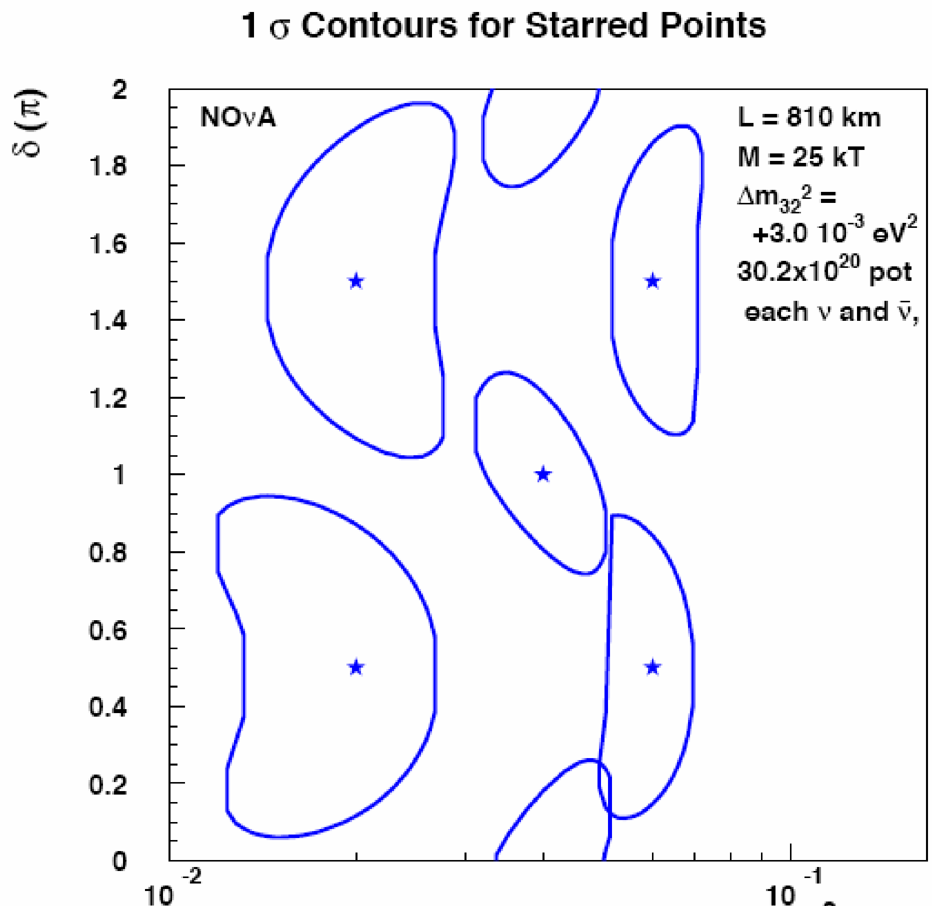


Δm^2 = 0.0030 eV^2

δ vs. $\sin^2(2\theta_{13})$ Contours: Linear vs. Logarithmic

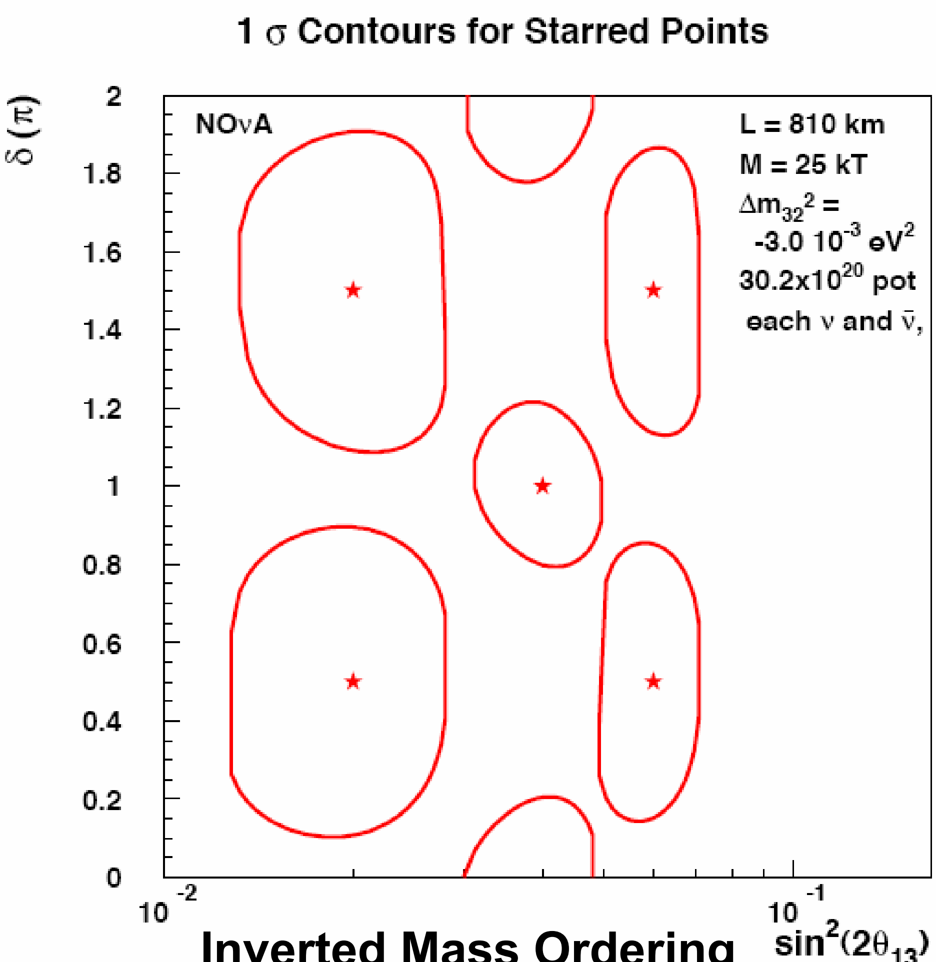


Linear scale

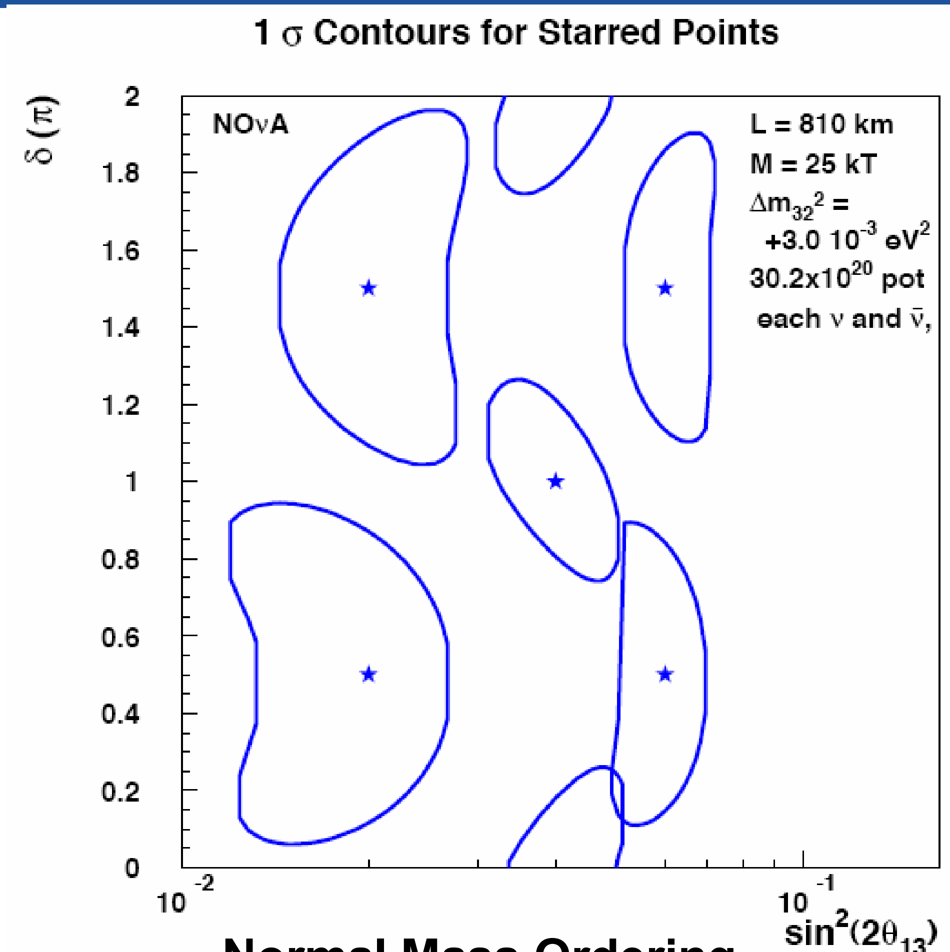


Logarithmic scale

δ vs. $\sin^2(2\theta_{13})$ Contours: Normal vs. Inverted Mass

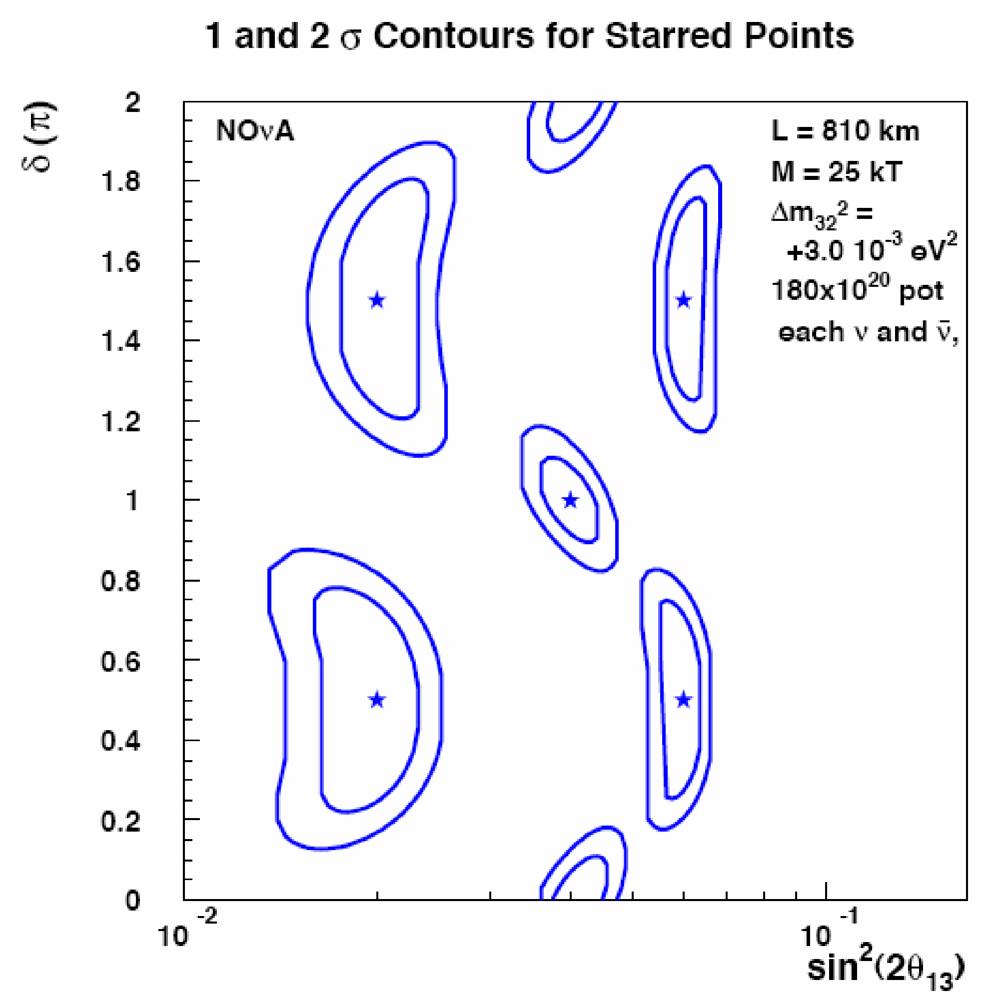


Inverted Mass Ordering



Normal Mass Ordering

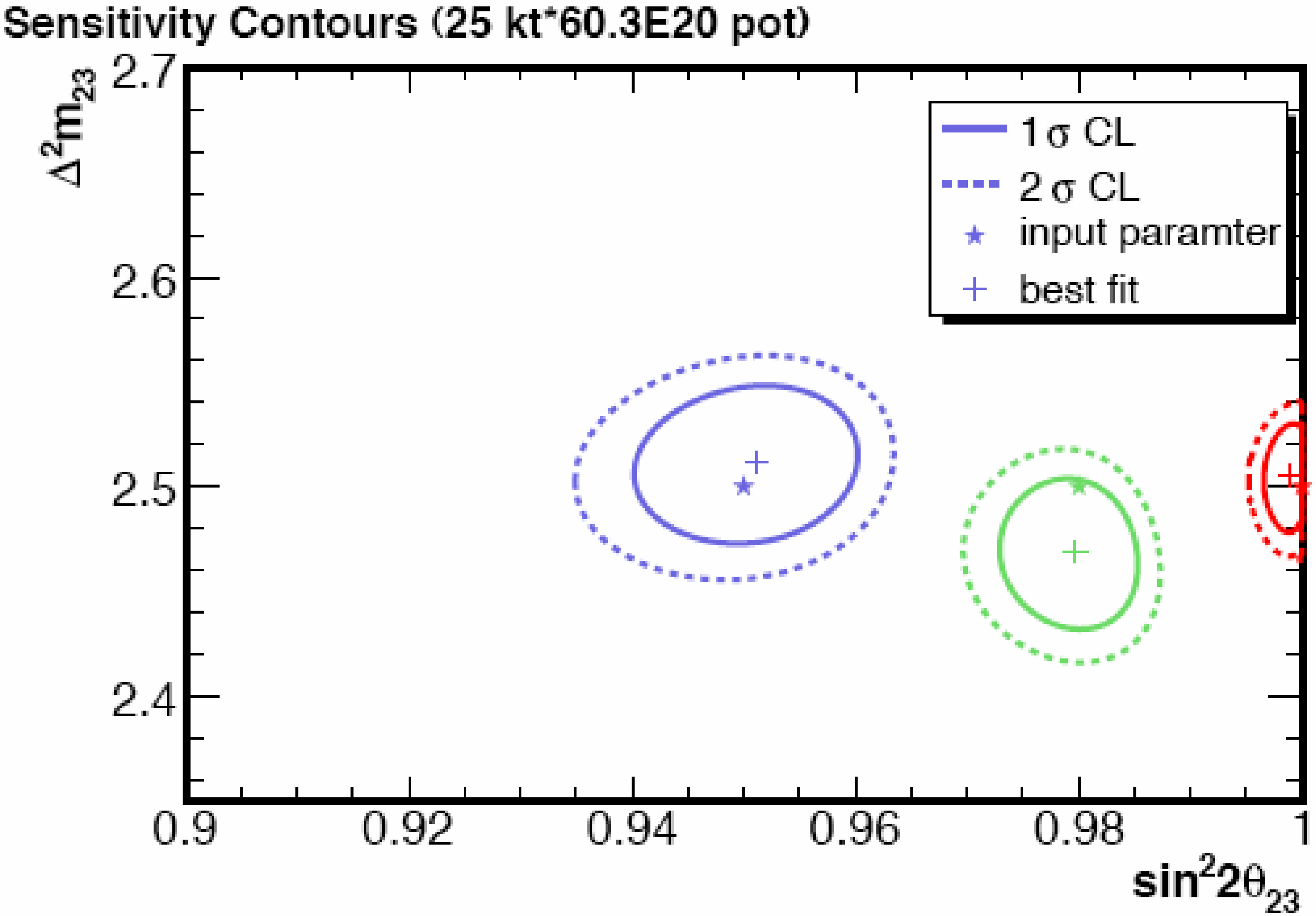
δ vs. $\sin^2(2\theta_{13})$ Contours: 6 x NOνA



Measurement of $\sin^2(2\theta_{23})$

- Whether the atmospheric mixing is maximal is an important question both practically (comparison of reactor and accelerator measurements) and theoretically (Is there a symmetry that induces maximal mixing?).
- The combination of the narrow-band beam and NOνA's excellent energy resolution allows it to do a high-precision measurement of $\sin^2(2\theta_{23})$ by measuring quasielastic ν_μ CC events.

Measurement of $\sin^2(2\theta_{23})$



If $\sin^2(2\theta_{23}) = 1$, then it can be measured to 0.004.

Otherwise, it can be measured to ~0.01.

Cost

- Two weeks ago, we had a CD-1 Review, which did not object to our cost estimate.
- The estimate is $ 226 M in FY2006 dollars, including $ 57 M in contingency. This corresponds to $ 247 M in actual year dollars.
- The cost in our proposal was $ 165 M in FY2004 dollars. We have submitted a detailed explanation of the differences to P5. Short answer:
  - R&D was not included in the proposal number
  - Increases in "maturity of estimate" partially countered by our recent descope from 30 kT to 25 kT
  - The rest is largely inflation, including the cost of oil

Cost

- Inflation calculation:
  - $ 165 M (minus oil-linked costs) FY2004 to FY2006 → $172 M
  - + R&D $ 12 M: $172 M → $ 184 M
  - + cost of oil FY2004 to FY2006 $ 32 M: $184 M x $216 M
- What about future increases in the cost of oil?
  - We have done a contingency analysis following DOE rules.
  - We have used DOE future cost of oil estimates and added an additional risk factor based on historical data using a Monte Carlo calculation and set the contingency at the 95% confidence level.

Schedule

- Apr 2006: CD-1 review. Unanimous recommendation to approve CD-1.
- Oct 2006: CD-2 review.
- Jan 2007: CD-3a
- Oct 2007: CD-3b, begin Far Detector enclosure
- Oct 2008: First module factory ready
- Jun 2009: Occupancy of the FD enclosure
- Nov 2010: 5 kT completed, start taking data
- Nov 2011: Far Detector completed

Sensitivity Schedule

- Estimated times to establish 3 σ sensitivity to $\theta_{13} \neq 0$ (normal mass ordering, $\Delta m_{32}^2 = 0.0025$ eV^2, $\sin^2(2\theta_{23}) = 1.$, $\delta = 0$):
  - Jan 2012, if $\sin^2(2\theta_{23}) = 0.05$
  - Nov 2012, if $\sin^2(2\theta_{23}) = 0.02$
  - Aug 2014, if $\sin^2(2\theta_{23}) = 0.01$

Conclusions

- **NOνA provides an effective utilization of the investment in the NuMI beamline.**
- **It is the right scale project for the present time. (More ambitious programs will need to wait for clarification of the ILC status.)**
- **It provides the information needed to plan the next step after NOνA.**
- **It provides the greatest reach in $\sin^2(2\theta_{13})$**
- **It provides the only information on the mass ordering.**
- **It provides low-precision data on CP violation in the lepton sector.**